UNIVERSITY OF ALBERTA

"BENTONITES AND THE GEOCHRONOLOGY OF THE BEARPAW SEA"

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ABSTRACT

Sampling of the bentonites included in the Upper Cretaceous Bearpaw Formation of southern Alberta and adjacent areas has provided material for a geochronological investigation of this marine sequence of strata. K-Ar dating of biotite and sanidine included in the bentonites has indicated that the Bearpaw Sea invaded most of the southern Alberta Plains 72-73 m.y. ago. The transgression of the sea was probably rapid and the base of the formation may be isochronous over most of the area, with the possible exception of areas in southern Saskatchewan and northern Montana where the sea might have transgressed somewhat earlier. The regressive upper boundary of the Bearpaw Formation is set at 68 m.y. in the westernmost Plains and at 66 m.y. further to the east in the Cypress Hills region. The geochronological picture is compatible with the paleogeography of the Bearpaw.

The bentonites intercalated with the normal sediments represent ash-falls produced by relatively remote volcanic eruptions. Study of the phenocrysts in the sand-size fraction, provided that contamination by detrital material has been negligible, has indicated that most of the bentonites are remarkably uniform in petrologic type and prevailingly andesitic. A source area is suggested in the eastern Cordilleran belt of northern Montana, where strong volcanism throughout most of the Late Cretaceous accompanied the gradual emplacement of the Boulder batholith. The andesitic nature of the Bearpaw bentonites is compatible with the granodioritic magmatism in the postulated source area.

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INTRODUCTION

The Upper Cretaceous sediments of the western Canada basin contain widespread bentonites. Thin, rather distinctive layers originated by ancient falls of volcanic ash, bentonites provide excellent time-stratigraphic markers which may be often followed and correlated over a wide area by their lithology and mineralogy. The potassium-bearing minerals of igneous origin contained in the clay matrix provide the means for K-Ar dating of the rock. The possibility of determining a reliable absolute age for strata in a sedimentary sequence enables geological events to be placed in an ordered succession on the absolute time-scale. Uncertainties and approximations left behind by normal stratigraphic studies may sometimes be solved and refined by the geochronological approach. Paleo-geographic synthesis has shown that the Bearpaw Sea represented the last westward marine invasion of western Canada during Late Cretaceous (Campanian) time. Dating of the bentonites included in the Bearpaw Formation provides, therefore, the way to estimate the duration of this episode.

Volcanism in western Canada, contributing to the normal sediments during Bearpaw time, is indicated by the presence of the ash-falls in the rock-column. The sources for the ash are determined by investigating the petrologic relationships between the bentonites and contemporaneous igneous activity on the margins of the Bearpaw basin. The phenocrysts contained in the sand-size fraction of the bentonite provide the basis for petrologic study.

PREVIOUS INVESTIGATIONS

The Bearpaw Formation was named from the Bearpaw Mountains of Montana by Hatcher and Stanton (1903). Detailed studies of the formation have been published in the following memoirs of the Geological Survey of Canada in conjunction with the geologic mapping of the southern Plains: Memoir 163 by Williams and Dyer (1930); Memoir 176 by Fraser, McLearn, Russell, Warren and Wickenden (1935); Memoir 221 by Russell and Landes (1940); Memoir 242 by Furnival (1946). Articles dealing with various aspects of the Bearpaw are included in the Dowling Memorial Symposium published in 1931. Loranger and Gleddie (1953), on the basis of its microfaunal content, have correlated the Bearpaw on both sides of the Sweetgrass arch in Alberta and Saskatchewan. More recently Evans (1961) and Caldwell (in press) have extended palaeontologic correlations from the Cypress Hills to the South Saskatchewan River Valley. The sedimentation in this area has been investigated by Hamilton (1962).

The presence of ash-falls intercalated with the normal sediments has been recorded by all the investigators. They have described to some extent the lithology of the bentonites and have used them as means of correlation. No detailed mineralogic study, however, has been done prior to the present work, with the exception of that of Sanderson (1931). With the establishment of radiometric methods of age determination interest in the bentonites as time-stratigraphic markers has been revived, particularly at the University of Alberta. Potassium-argon dates of the Upper Cretaceous bentonites in Alberta have been recently summarized by Folinsbee, Baadsgaard and Lipson (1961).

CHAPTER ONE

BEARPAW FORMATION - THE BEARPAW SEA

Outcrop distribution of the Bearpaw Formation in southern Alberta and adjacent areas

Large areas of the western Great Plains in southern Alberta, southern Saskatchewan and across the International Boundary in northern Montana are underlain by marine shale of the Bearpaw Formation (Upper Cretaceous). The outcrop distribution of the Bearpaw in the region under consideration is indicated in Figure 1.

The Bearpaw crops out on both sides of the broad positive feature known as the Sweetgrass arch. Along the axial part of the arch it has been removed by erosion leaving the Belly River and lower formations exposed at the surface. On the west flank the Bearpaw shale forms a continuous belt, dipping gently westward into the Alberta syncline. Southward the belt narrows progressively until in Montana it becomes no wider than a few miles. South of Cutbank the outcrops become discontinuous at the edge of the disturbed foothills belt. From the eastern side of the Sweetgrass arch the Bearpaw strata dip away imperceptibly to the east, displaying a ragged contact-line with the lower formations. Further eastward the Bearpaw loses most of its identity and merges into the thick comprehensive series of the "Montana" marine sediments. In the Cypress Hills and in southwestern Saskatchewan several large outliers are remnants of a cover of younger rocks well above the general level of the plains, developed on the softer, more easily eroded shales of the Bearpaw. The younger cover reappears at the top of the Bearpaw in the region of the Missouri Coteau.

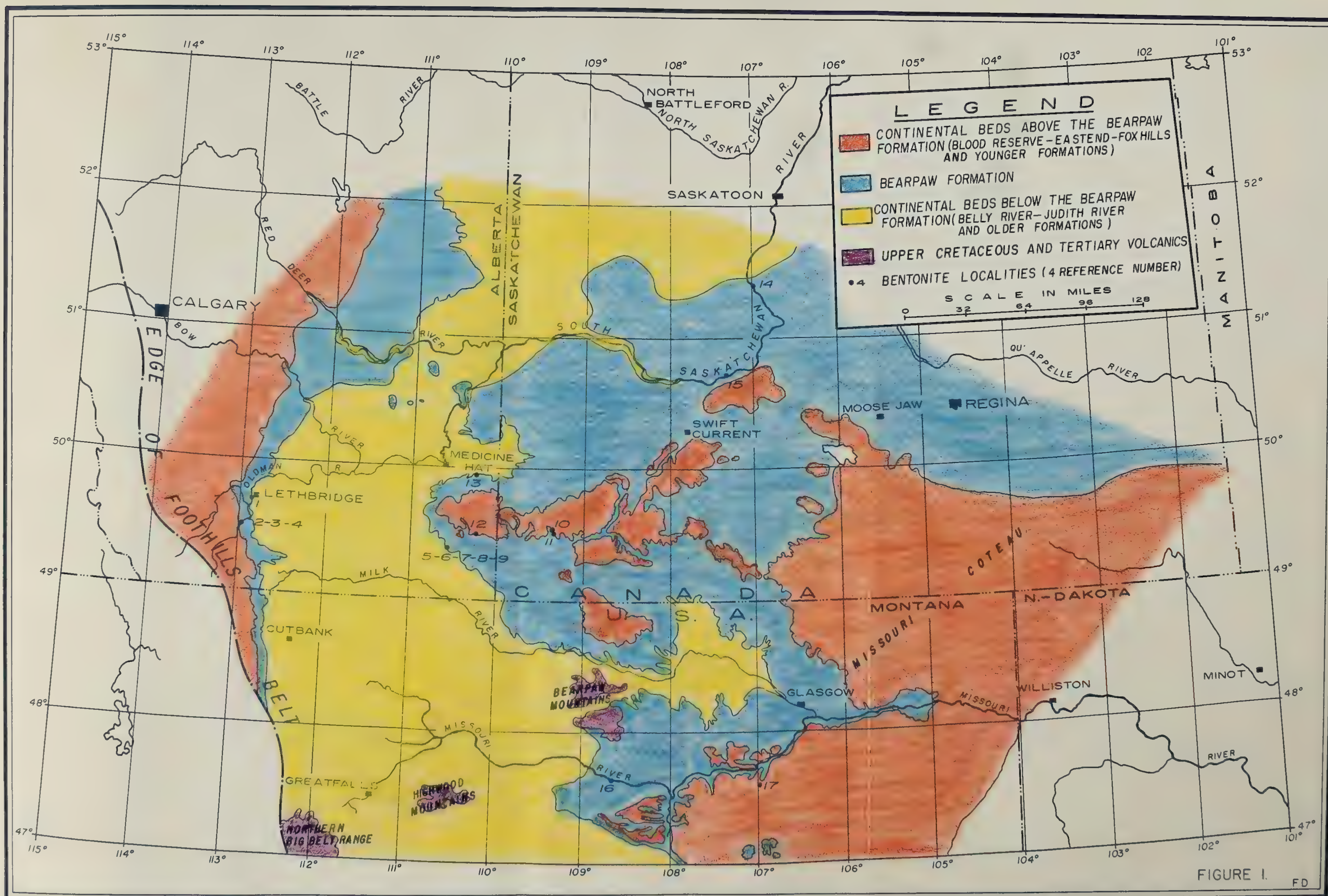
LEGEND
CONTINENTAL BEDS ABOVE THE BEARPAW FORMATION (BLOOD RESERVE-EASTEND-FOX HILLS AND YOUNGER FORMATIONS)
BEARPAW FORMATION
CONTINENTAL BEDS BELOW THE BEARPAW FORMATION (BELLY RIVER-JUDITH RIVER AND OLDER FORMATIONS)
UPPER CRETACEOUS AND TERTIARY VOLCANICS
•4 BENTONITE LOCALITIES (4 REFERENCE NUMBER)
SCALE IN MILES
0 32 64 96 128
NORTH BATTLEFORD
SASKATOON
CALGARY
LETHBRIDGE
MEDICINE HAT
SWIFT CURRENT
MOOSE JAW
REGINA
CUTBANK
GREAT FALLS
GLASGOW
WILLISTON
MINOT
ALBERTA
SASKATCHEWAN
MANITOBA
MONTANA
N.-DAKOTA
CANADA
U. S. A.
EDGE OF FOOTHILLS BELT
BEARPAW MOUNTAINS
HIGHWOOD MOUNTAINS
NORTHERN BIG BELT RANGE
COTEAU
BATTLE RIVER
NORTH SASKATCHEWAN R.
RIVER
RED DEER RIVER
BOW RIVER
SOUTH SASKATCHEWAN
QU' APPELLE RIVER
OLDMAN R
MILK RIVER
MISSOURI RIVER
1
2-3-4
5-6-7-8-9
10
11
12
13
14
15
16
17
FD

FIGURE I.

Figure 1. Out
form

Lithology and Palaeontology

The Bearpaw Formation consists mostly of dark-colored marine shale with minor intercalations of sandstone, either marine or non-marine. The shale is typically dark-grey to brownish-grey, is soft, and has a distinct flaky appearance on the weathered exposure. The fresh shale has a blocky habit. Clay-ironstone concretions are scattered within the entire formation and are commonly concentrated to form continuous or semi-continuous bands which may be traced for several miles (Byrne and Farvolden, 1959). The larger concretions are spheroidal to lentiform, are frequently silty and limy and often contain fossils. Selenite crystals and small nodular concretions of barite are locally abundant. The shale occasionally may be bentonitic and is in that case of somewhat lighter-grey color.

Sandy shale zones and sandstone beds at several levels are common at some localities. In the Cypress Hills, for instance, they tend to be concentrated in the upper part of the formation, in the South Saskatchewan River valley they form two major intercalations in the shale. They may be eventually recognized as stratigraphic members. The sandstones are usually fine-grained, poorly indurated and argillaceous.

Marine megafossils are abundant at some localities and are found mostly in the shale. Some are characteristic, fairly restricted in range, and can be used for correlation; most, however, are either too sparse or geographically restricted or too long-ranging to be reliable. Large ammonites are conspicuous. Several species of *Acanthoscaphites* are found in the upper horizons and *Acanthoscaphites nodosus* permits the correlation of the fauna with the Campanian of Europe (Landes, in Russell and Landes, 1940). *Baculites ovatus*, *Baculites compressus*, *Placenticeras meeki* and *Placenticeras intercalare* are common throughout the whole formation. The presence of *Baculites compressus* together with an abundance of the associated

ammonite fauna is the best palaeontologic index of the Bearpaw. The Pelecypoda are represented by species of Inoceramus, Yoldia, Pecten and Nucula. Some sands are locally very rich in Arctica ovata or in species of Ostrea. The reader is referred for greater detail to the work of Russell and Landes (1940).

The microfauna has been described by Loranger (Loranger and Gleddie, 1953) in areas on both sides of the Sweetgrass arch. She has recognized the following zones:

From top to bottom.

Gyroidina sp. and Ostracoda Zone

Glauconite "zone"

Ammodiscus sp. Zone

Anomalina sp. Zone

Plectina smithia Zone

Tritaxia crydermanensa Zone

In the area west of the Sweetgrass arch faunas of the two higher zones and part of the third are already included in the Blood Reserve and Lower St. Mary River indicating the equivalence of these formations to the upper part of the Bearpaw on the other side of the arch. The microfaunas in south Saskatchewan have recently been studied by Evans (1961) and by Caldwell (in press).

Bentonites in the Bearpaw Formation

Bentonite beds are widespread in the Bearpaw. They range in thickness from a fraction of an inch to several feet. The bentonites are typically lighter colored than the including shale. The colors of individual beds differ slightly from each other, the most common being greyish-yellow, pale greenish-yellow or pale olive (Rock

color chart, Geol. Soc. America, 1951). The bentonites are not, or are uncommonly lithified by cementing material. However in outcrop they may display greater competence than the shale. It is suggested that the large amount of water absorbed by the swelling bentonite-clays would tend to increase the coherence by holding the particles together. In the Cypress Hills area, benches which are tens of yards wide, have been carved by erosion, a bench corresponding to each bentonite. Evidently the bentonite layers offer some sort of protective cover to the shale underlying each of them. Undisturbed bentonites usually show sharp contacts with the including shale, especially the lower contact. The upper contact is often more gradational and laminations and even shale partings have been definitely observed in some beds. The bentonites react to post-depositional deformation as an exceptionally incompetent material even with respect to the shale. The great plasticity favours flowage deformation. Pinching and swelling, contortion, disruption of the beds, as well as injection of bentonite material into the shale have been seen at several localities.

The bentonite layers are also extremely impermeable and as such are often the loci for collection of ground-water. On outcrop faces in cliffs, a line of small springs often marks the upper surface of the beds. Even when debris or vegetation conceal the outcrop it is not uncommonly found that a bentonite bed may be picked by observing the band of more luxuriant vegetation which follows the moisture line.

Continental strata above and below the Bearpaw Formation

The deposition of the Bearpaw was preceded and followed by continental sedimentation. Table I shows the relationships of the Bearpaw to the adjacent formations in the studied area. The overlying formations have gradational and diachronous contact with the Bearpaw, gradually replacing this formation to the west and north. No break in sedimentation appears to occur between the Bearpaw

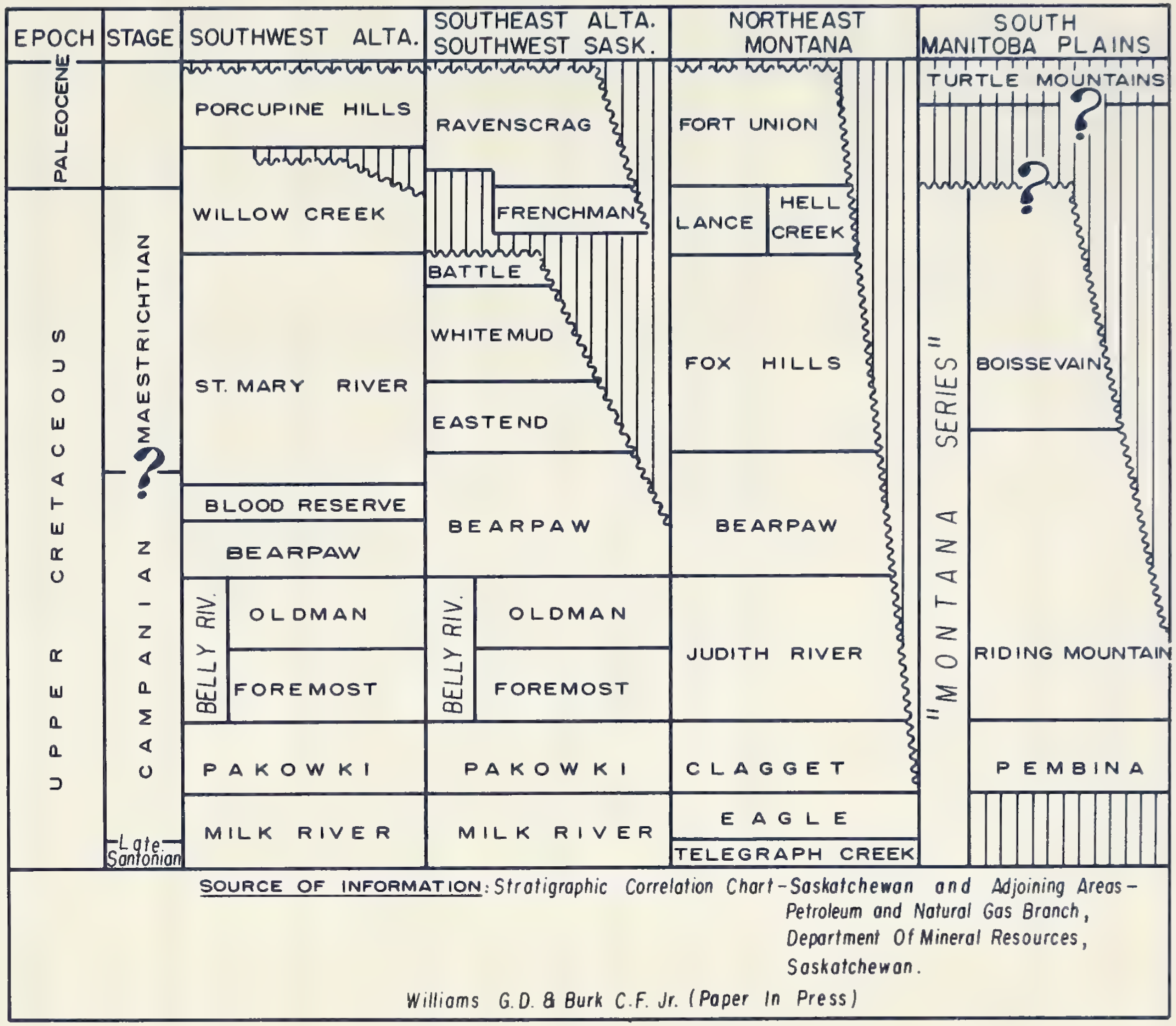

Table I. Bearpaw and contiguous formations in southern Alberta and adjacent areas

and the underlying Belly River. These continental deposits consist mainly of fine-grained sandstone and shale laid down apparently on a flat alluvial plain. The coal and lignite seams which are common in the topmost part of the Belly River section and extend continuously over wide areas seem to indicate the existence of a swampy and flat surface which was readily and quickly flooded by the advancing sea. The base of the Bearpaw is generally set at the top of the highest occurrence of the organic non-marine shale.

The Bearpaw Sea

It is well known that a great epicontinental sea persisted throughout the entire Cretaceous over much of what is now the Central Plains region of North America. It was a huge sea arm during the Turonian age occupying a continuous north-south trough from the Gulf of Mexico to the Arctic Ocean (Stelck, 1958). The sedimentation was mostly fine clastic material ("Dakota", "Colorado" and "Montana" shaly series) except along the westernmost shores where the Cordilleran geanticline periodically supplied coarser debris to marginal alluvial and delta plains. During Montanan time the Cordillera entered a new series of orogenic pulses which were to continue throughout the period and well into the Tertiary (Baadsgaard *et al.*, 1961) and during this time advances or retreats of the alluvial shores and the sea respectively became quite frequent. At each renewal of erosion, great amounts of debris dumped into the sea built a wide front of coalescing deltas which pushed back the sea. At times when the erosion and deposition lessened, the sea readvanced to the west. The Bearpaw Sea was the last major marine transgression (Figure 2) of the Cretaceous. Apparently the sea advanced rapidly from the east across the flat alluvial surface of the Belly River strata. The transgressive surface at the base of the Bearpaw Formation is

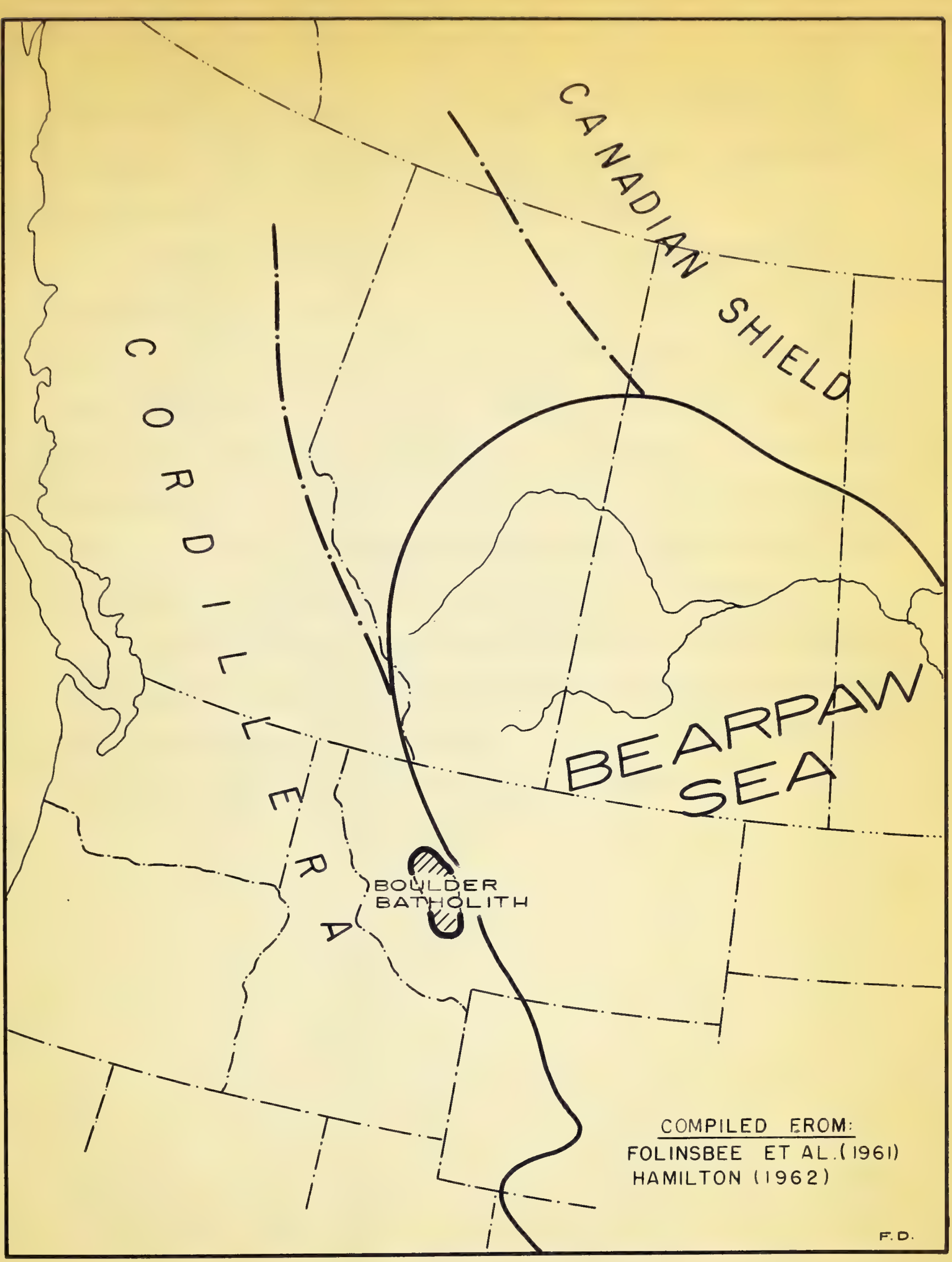

Figure 2. Maximum probable extent of Bearpaw Sea

generally accepted as isochronous (Russell and Landes, 1940; Furnival, 1946), except perhaps in central southern Saskatchewan, eastern Montana and adjacent areas where the movement may have been more progressive.

A definitive eastward growth of the alluvial plains finally drove the Bearpaw Sea out from most of the area it had earlier occupied. The seas retreated continually until by the end of the Cretaceous they had shrunk to a remnant in the southeast (Cannonball Sea) never again to spread over the Canadian Plains (Folinsbee, et al., 1961). The regression took place slowly and apparently continental sediments were already accumulating in the west while marine Bearpaw muds were still being deposited in the east. Marine tongues in the continental series above the Bearpaw indicate also that minor oscillations interrupted the withdrawal of the sea.

Intense volcanism occurred during the Late Cretaceous in the Cordilleran region (Folinsbee, et al., 1961) and great quantities of ash were periodically ejected by the volcanoes which stood on the margin of the sea. The ashes transported by the high-altitude winds fell into the sea and settled on large areas of the sea floor.

CHAPTER TWO

AREAL STRATIGRAPHY

Field reconnaissance and sampling

A number of bentonites from the Bearpaw Formation were sampled by the writer in the company of Dr. R.E. Folinsbee during reconnaissance excursions in southern Alberta and southern Saskatchewan in the summer of 1962. Other bentonites collected during previous field seasons were obtained through the courtesy of Drs. Folinsbee and Baadsgaard. The localities of sample collection are shown in Figure 1. For sampling, undisturbed and unweathered exposures were sought to obtain unaltered bentonite for dating. The samples were collected by channelling a certain width of the outcrop, or when feasible by stripping the material overlying the bentonite and collecting the freshest rock. Often it was necessary to dig deeply into the outcrop face to reach promising fresh material. The entire thickness of the bed was generally sampled, the strata being usually not over a foot in thickness. Much care was taken to avoid any contamination from the adjacent shale. At least 20 pounds of material were collected from each bentonite.

The partial stratigraphic sections sampled were eventually tied into composite published sections of the Bearpaw Formation for each area visited with the aid of horizon-markers, such as the concretionary "zones", fossil-bearing layers and even bentonites themselves. The data pertinent to four type areas have been assembled into the idealized stratigraphic columns represented in Figure 3. The sampled bentonites are indicated in each column and detail on their locations and stratigraphic position is given in the appendix.

IDEALIZED STRATIGRAPHIC COLUMNS
BEARPAW FORMATION

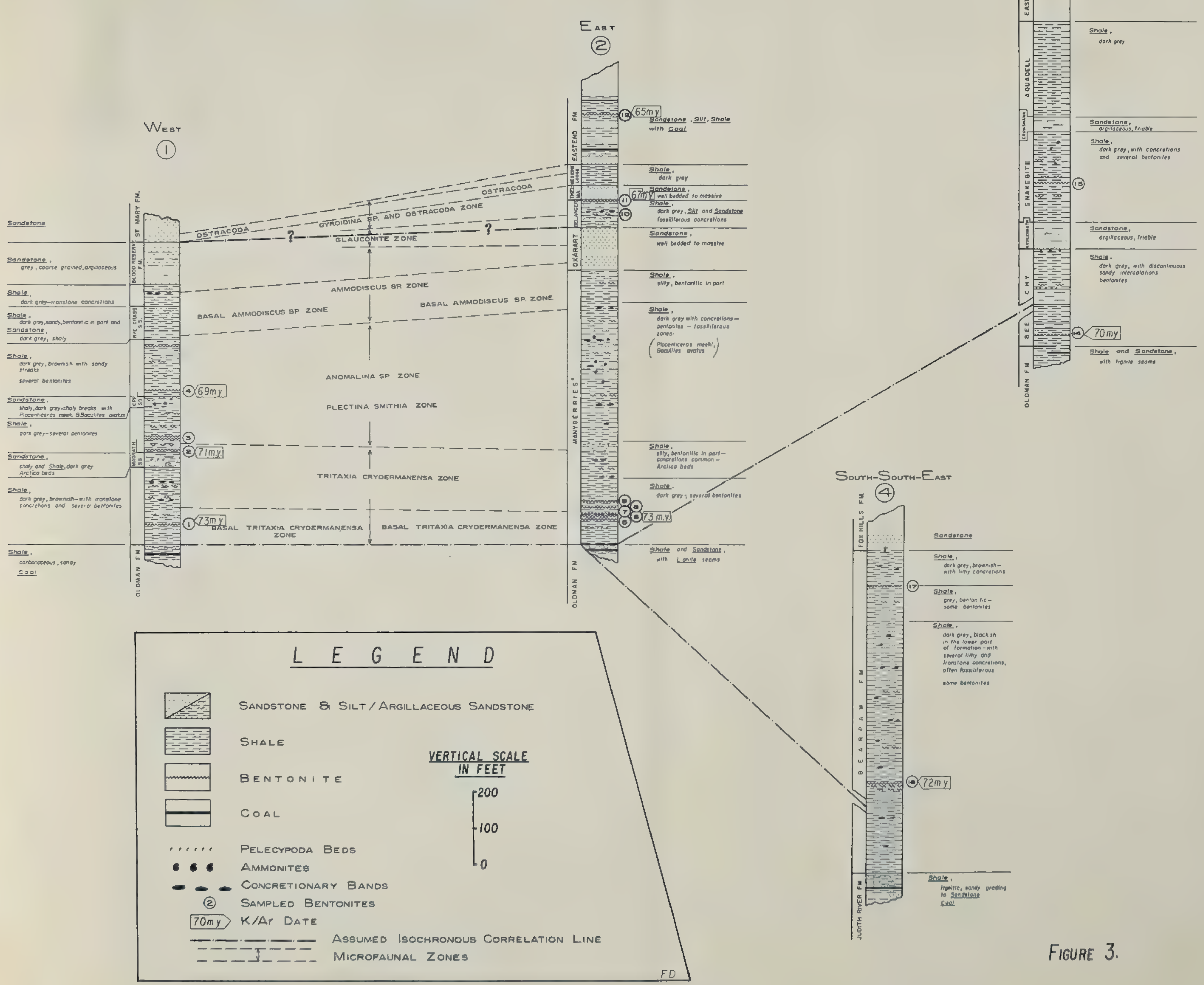

FIGURE 3.

Figur

St. Mary River - Lethbridge area

Columnar section No. 1 shows the type-stratigraphy of the Bearpaw Formation west of the Sweetgrass arch. The stratigraphy of this area has been described by Link and Childerhose (1931) and by Russell and Landes (1940). Numerous good sections are exposed along the watercourses which cut across the Bearpaw outcrop belt. Four bentonites were collected from outcrops, measured and described in detail by Russell and Landes, along the St. Mary and Oldman Rivers. The Bearpaw has here an overall thickness of 720 feet.

Cypress Hills area

Columnar section No. 2 of Figure 3 indicates the Bearpaw stratigraphy east of the Sweetgrass arch in the Cypress Hills region. The thickness for the entire Bearpaw is here 1050 feet (Loranger and Gleddie, 1953). Furnival (1946) gave an estimated thickness of between 940 and 1000 feet. The Bearpaw consists in this region of shale and minor intercalated marine and non-marine regressive sandstones and lies between the Oldman and the Eastend Formations. Its base is drawn at the top of the highest organic shale bed of the Oldman. As shown the formation is divided into five members. Three sandstones intervals occur in the upper 300 feet of the formation above the shaly section shown as "Manyberries". In ascending order these are the Oxarart, the Belanger (sandstone and silt with abundant interbedded shale) and the Thelma Members. These members become either very thin or absent towards the east. The topmost member, the Medicine Lodge Member (shale locally interbedded with very fine sandstone or siltstone) represents a transition to the sandstone of the Eastend Formation. Five bentonites were collected in the basal

member of the Bearpaw exposed in the badlands east of Manyberries, on the southwestern slope of the Cypress Hills (Russell and Landes, 1940). Two bentonites were collected from the Belanger Member on the southern slopes of the Cypress Hills in Saskatchewan. An additional sample was collected from the ashy bentonite recorded by Byrne (1955) at Irvine, Alberta, in the basal part of the Bearpaw. One bentonite was sampled in the Eastend Formation on the southwestern slopes of the Cypress Hills, Alberta. As no break in sedimentation apparently occurred between the Bearpaw and the Eastend Formation, a date yielded by this bentonite might be of considerable aid in estimating the time limit of the underlying upper Bearpaw, devoid, in this area, of suitably well-exposed bentonites.

South Saskatchewan River Valley area

The Bearpaw Formation in the South Saskatchewan River valley consists essentially of dark grey, poorly indurated shale interrupted by two main intervals of friable sandstones. The sequence is about 900 feet thick (Hamilton, 1962). According to Caldwell (in press) the Bearpaw in this region is divisible into five members. The basal Beechy Member rests on the Oldman Formation and is mainly formed of shale and discontinous intercalations of sands. The Ardkenneth, Snakebite, Cruikshank and Aquadell Members follow in ascending order. The Ardkenneth and Cruikshank Members as indicated in columnar section No. 3, Figure 3, form the two main sandy intercalations within the Bearpaw. The Snakebite Member contains numerous bentonites, but bentonites are common throughout the entire Bearpaw section. The shales of the Aquadell Member pass, with gradational contact, into the sandstone of the overlying Eastend Formation. The bentonites studied for this area were collected respectively from the lower part of the Beechy Member (Outlook bentonite) and from the middle of the Snakebite Member (locality Beechy Ferry).

Northern Montana

Two bentonites were sampled in the Bearpaw Formation of northern Montana. Their stratigraphic position is shown in columnar section No. 4, Figure 3. The Bearpaw beds of this region and of southern Alberta are correlative, on the basis of stratigraphic position and fauna (Furnival, 1946). Though no detailed data are available at this time the total thickness of the formation was estimated at 900 feet (Reeves, 1924). From the works of Cobban and Reeside (1952) and Robinson et al. (1959), who studied the Bearpaw in Montana and Wyoming, and assuming that the higher sampled bentonite is equivalent in position to the Kara Bentonitic Member of southern Montana (R. Sloan, personal communication) the presence of 900 feet of Bearpaw section in the area does not seem unlikely.

Correlations

Simplified correlations, on the basis of the information reported in the literature, have been drawn between the various columnar sections of Figure 3. The base of the Bearpaw Formation between columnar section No. 1 and No. 2 is drawn as an isochronous line. As Russell and Landes (1940) have pointed out "it seems probable that the base of the formation is very nearly the same age ... (within the present area), as the widespread development of the Lethbridge Member at the top of the Oldman Formation (coal-bearing strata) and the abrupt character of the base of the Bearpaw suggest that the sea came in rather quickly". In the case of the top of the Bearpaw the upper beds become progressively younger from west to east. The Bearpaw in the St. Mary River-Lethbridge area is 720 feet thick and overlain by 115 feet of Blood Reserve Sandstone for a cumulative thickness of 835 feet (Russell and Landes, 1940). The Blood Reserve is strikingly similar in lithology

to the Oxarart Member of the Cypress Hills region, wherein the thickness of the Bearpaw to the top of the Oxarart is variously estimated from 800 (Furnival, 1946) up to 875 feet (Loranger and Gleddie, 1953). Their lithologic resemblance and the almost identical stratigraphic position suggest therefore their correlation. This conclusion is further substantiated by the microfaunal zoning of Loranger (1953). The uppermost strata of the Bearpaw Formation in the Cypress Hills area are definitely replaced westward by continental sandstones and have their time-equivalents in the Lethbridge-St. Mary area in the St. Mary River Formation (Furnival, 1946, Russell, 1950).

In the South Saskatchewan River valley the lower 120 feet of Bearpaw Formation, according to Caldwell's faunal correlations (Caldwell, personal communication), are probably equivalent to the Oldman Formation in the Cypress Hills. The Bearpaw marine sedimentation evidently began in this area somewhat earlier than in southern Alberta.

CHAPTER THREE

PETROLOGY OF THE BENTONITES

General characters

A bentonite may be essentially defined as an argillaceous rock with a residual pyroclastic texture, the clay-mineral of which derives mainly from the breakdown and alteration of the vitreous portion of the original volcanic material. The source material is usually a volcanic vitric ash or tuff (Pirsson, 1915; Carozzi, 1960) deposited under water. The great permeability of the ash to the overlying water seems to be an essential factor for the alteration required to produce bentonites. Dense vitreous rocks, such as lavas, do not appear to give rise to any clay-rock truly resembling the bentonites. An occurrence has been observed by Ross and Hendricks (Ross and Hendricks, 1945) in which weathering of basaltic lavas has produced a nontronite clay preserving much of the texture of the lava (vesicles, shape of the minerals), but this is a rare occurrence and the texture points unequivocally to a non-pyroclastic origin. In the Bearpaw bentonites there appears to have been a definite manner of transport and deposition of the source material: volcanic explosive ejection, high wind-long distance transportation, settling in water, very little or no reworking, followed by alteration *in situ*. In the general case it is known that volcanic ejecta may accumulate either on land or on the sea floor. When settling in the sea the ashes are subject to reworking by the currents or by the waves and on the land, of course, they are even more subject to erosive agents, though it has been shown that thick ashes can be preserved *in situ* interbedded with continental sediments. The ashes are, therefore, often redeposited in lakes or carried to the sea, and in this process become usually admixed with normal detrital material from the surrounding

country rocks and incorporate fossils and carbonaceous material. Layered texture becomes characteristic. Such lamination is on the other hand rather unusual in "in situ" bentonites. Mixed rocks are eventually produced through an entire series of gradations, and by the alteration of the glass contained are transformed into bentonitic sediments (Ross, 1928). The Bearpaw Formation contains bentonitic shales at several levels. It seems unlikely that, if bentonitic material had been reworked after the glass had been altered to clay it would be possible to recognize the resulting clay as definitely of bentonitic origin.

The bulk of a bentonite is usually clay. The clay is produced soon after deposition by the hydrolysis of the unstable vitric material and exchange with the cations available in the environment; the material is originally permeable and presents large surface to reaction. In general montmorillonite is produced (Ross, 1928; Byrne, 1955; Slaughter and Earley, in press) but several other clay-minerals have been identified in bentonites; illite, mixed layer montmorillonite-illite, chlorite and kaolinite. Illite and mixed-layer minerals are next in abundance to montmorillonite. Mineralogy of the clays was not studied in the present thesis but from a few observations reported in the literature (Byrne, 1955; Byrne and Farvolden, 1959) it might be reasonably expected that montmorillonite might be the predominant clay, with perhaps some illite and mixed-layer clays. According to Keller (1956) the best conditions for the formation of montmorillonite are the retention in the system of both silica (flocculated by Ca^{++} and Mg^{++} ions) and of cations of magnesium, calcium and iron, under alkaline condition in standing water. If potassium ions are retained in quantity illite could form instead of, or together with montmorillonite or mixed-layer minerals. Weaver (1953) has advanced the hypothesis that the mixed-layer clays could also have been formed later during epigenesis by the exchange action of potassium bearing solutions percolating through the system.

Softness, plasticity and swelling properties are imparted by the clays, and clays are therefore important in the bentonites. However clays are not the main and best characterization of the rock type. Other characteristics, mainly the relict textural features, appear to be better guides in pointing out the genetic relationship with the volcanic ash, the nature of the source magma, the degree of contamination and the mode of transport. In the present work, in which the bentonites are studied as potential chronologic marker-beds, the latter characteristics are of paramount importance. Attention is therefore concentrated on the crystalline material almost invariably present within the clayey bulk of the bentonites. Such material represents the more stable phenocrysts of the ejected magma, more or less shattered by the explosion but mostly unattacked by the alteration, which on the other hand has transformed the glassy counterpart into clays. The mineral suite consists of typical volcanic crystals; nevertheless there is often also a part which is of detrital admixed origin. In this case the problem arises of differentiating between the two mineral suites. Several criteria are available which are definitely helpful: The habits and appearance of the crystals, the trace of abrasion, the mineral inter-relationships and the essential simplicity of pure volcanic mineral assemblages.

In relatively young bentonites, such as the studied Upper Cretaceous bentonites, relict glass is sometimes present, together with coarse crystalline material. The glass is found as shards produced by the explosive fragmentation of the magma groundmass and often appears fresh. Actually gradations of bentonites to unaltered vitric ashes are not uncommon. In older strata, however, for instance in the Palaeozoic bentonites studied by Weaver (1953), by Smith (1960) and by others, the shards have been subjected to long continued devitrification and what is left are fine-grained quartz and feldspar aggregates showing a feeble aggregate

polarization under the microscope. The "bogen texture", a relict texture in the clay groundmass which has preserved the shape of the shards, reveals that the aggregates were originally glass. It is evident from the above observations that the glass can survive even in beds which are partially transformed into bentonite. It appears probable that something must have hampered the alteration process. If we assume that "bentonization" took place soon after deposition, when the ash beds were still in contact with and readily permeated by the overlying fluids, we may be able to visualize reasonably how, for instance, a fast accumulation of mud or very fine ash covering the bed soon after deposition could have hindered the subsequent alteration, which had to take place from that point on in a restricted system.

Preparation of samples

The amount of relatively coarse material (crystalline minerals and glass fragments) in the average bentonite is usually small. It was advisable therefore to start working with a large sample of several pounds. The procedure varied but commonly was as follows: The large initial sample was split into two sub-samples by quartering. The larger sub-sample was used to separate minerals for mineralogic study and for dating. The smaller sub-sample, commonly of 200 grams, was used to separate quantitatively the coarse material for size and mineral distribution study. By using a single large sample for both purposes the chances were that losses in handling so much material would be far too great for the accuracy of the results. The sub-samples were soaked in water, disaggregated thoroughly and wet-sieved. After drying, the coarse materials separated were screened anew by Ro-Tap sieving machine and sized to plus 60, 60-120, 120-170, 170-230, 230-270, 270-325 and minus 325 mesh (U.S. standard sieve sizes). Attempts to make a size-

analysis of the "clay-size" material (minus 325 mesh) by the pipette method failed because of the clays aggregating in the suspension.

Heavy liquids and the Frantz isodynamic separator were used to obtain mineral concentrates from the sized materials of the larger sub-samples. The technique adopted was essentially that described by Orr (1959) and by Smith (1960). The use of the centrifuge often helped in fractionating the finer-sized materials. A geometric setting of 18° "slope" and 7° "tilt" for the Frantz isodynamic separator was commonly adopted but the settings varied according to the particular magnetic character of the minerals being run. Feldspars, quartz, glass fragments, gypsum were separated into various "light" fractions (specific gravity less than 2.96 and lighter) with tetrabromethane and tetrabromethane-acetone mixtures. The "heavies" (specific gravity greater than 2.96) were further sorted with methylene iodide (specific gravity 3.33).

Finally the following fractions were obtained:

"Light-fractions"

1. The light-fraction with specific gravity less than 2.45, consisting chiefly of glass*, and gypsum.

2. The light-fraction with specific gravity between 2.45 and 2.57 which consisted chiefly of K-feldspar.

3. The light-fraction with specific gravity between 2.57 and 2.96, mainly formed of plagioclase feldspar, quartz, muscovite (may be concentrated with Frantz separator set at 1.7 amp.).

"Heavy-fractions"

1. Specific gravity greater than 2.96
Frantz isodynamic separator set at 0.2 amp.
Essentially ilmenite, magnetite, with some biotite.

2. Frantz set at 0.4 amp.
Essentially biotite, some amphibole and pyroxene.

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*The most important minerals as for their abundance or frequency, are underlined.

3. Frantz set at 1.7 amp.
   Essentially amphibole, pyroxene, titanite, garnet, epidote, rutile, some muscovite (?).

4. Non-magnetic fraction remaining. Made up of zircon, apatite, barite, epidote.

5a. The heavy non-magnetic fraction was separated in methylene iodide, and the "heaviests" (specific gravity greater than 3.33) were mainly zircon and barite.

5b. The apatite was left in the lighter part of the heavy non-magnetic fraction.

The separations were not always as clean-cut as the above description would imply, however with much care and repeated runs it was possible to obtain essentially pure separates. Biotite and zircon are relatively easy to separate, but K-feldspar, for instance, when scarce in the sample, requires much more care and patience. In all the stages of the separations the samples were examined in immersion liquids under the microscope to determine the next step. Permanent mounts of the separates were made for microscope study using Canada balsam (index 1.54). The "heaviest" non-magnetics were mounted also in aroclor (index 1.67). Microsplit portions of the "200 gram" sub-sample coarse material were mounted in balsam on graticule glass slides for grain counting.

Mineralogy of the "coarse fraction"

Each fraction of sample, mounted on glass slides, was examined microscopically and the minerals identified. Table II indicates the total coarse mineral assemblages of twelve representative bentonites. The minerals are grouped as essential components, detrital components (or contaminants) and authigenic minerals. The essential components are further subdivided for facility of description into light and heavy minerals.

TABLE II COARSE MINERAL ASSEMBLAGES OF STUDIED BENTONITES

	Essential minerals											Detrital and accidental				Authigenic			
	Plagioclase (Andesine)	K-feldspar	Quartz	Volcanic glass (shards)	Biotite	Hornblende	Hypersthene	Zircon	Apatite	Titanite	Magnetite and Ilmenite	Muscovite	Epidote	Garnet	Rutile	Barite	Calcite	Gypsum	Limonite
Leth bridge No. 1	x	x			x	o	x	x	x		x	x	x	x		x		x	x
St. Mary Double bed	x	x	x		x			x	x		x				x	x	x		
Manyberries No. 1	x	x	x		x			x				x				x		x	x
Manyberries No. 2	x	x			x		x	x	x		o	x				x			x
Manyberries No. 3	x	x			x			x	x		x	x	x			x			x
Manyberries No. 4	x	x			x		x	x	x		x	x	x			x			x
Manyberries No. 5	x	x	x		x			x	x		x					x			
North Fork Creek	x	x	x	x	x	x		x	x	x	x		x				x		
Outlook	x	x						x	x							x			x
Beechy Ferry	x	x			x	o		x	x	x	o					x			x
J. Kipp	x	x	x		x			x	x		o					x	x	x	x
Irvine	x			x	x						oo	x					x		

x = Free Crystals. o = Only as inclusions in Plagioclase. oo = Only as inclusions in glass shards

The mineral suite displayed is most distinctive. It is essentially simple, uniform and formed of volcanic minerals such as occur in volcanic ashes. The volcanic-type minerals are by far the most abundant and are usually distinctive in habit with euhedral forms common. The detrital-type components are subordinate in abundance and their distribution is not uniform. They commonly show traces of attrition and are in most cases not typical of volcanic rocks but may have been contributed by either metamorphic, igneous intrusive or sedimentary terranes. The mineralogic characterisitic and the mineral relationships of the third group show that they are authigenic minerals that have been formed within the rock after deposition.

Essential Components

In all the studied bentonites the most abundant essential minerals are the plagioclase feldspars, together with lesser amounts of biotite and sanidine. Other minerals, either "lights" (quartz) or "heavies" (zircon, apatite, titanite, magnetite, amphibole) are present in minor to trace amounts. The glass shards, when preserved, may form a very large portion of the volcanic material (as in the ashy bentonite at Irvine). Abundant glass was originally contained in all the bentonites and its abundance at present reflects merely an accidental preservation during the diagenesis of the rock.

Light Minerals:

Plagioclase feldspars

The plagioclase feldspars constitute the greatest proportion of the coarse crystalline material from all the studied Bearpaw bentonites (Figure 4). Only in a single occurrence is the plagioclase percentage very low (Irvine ashy bentonite),

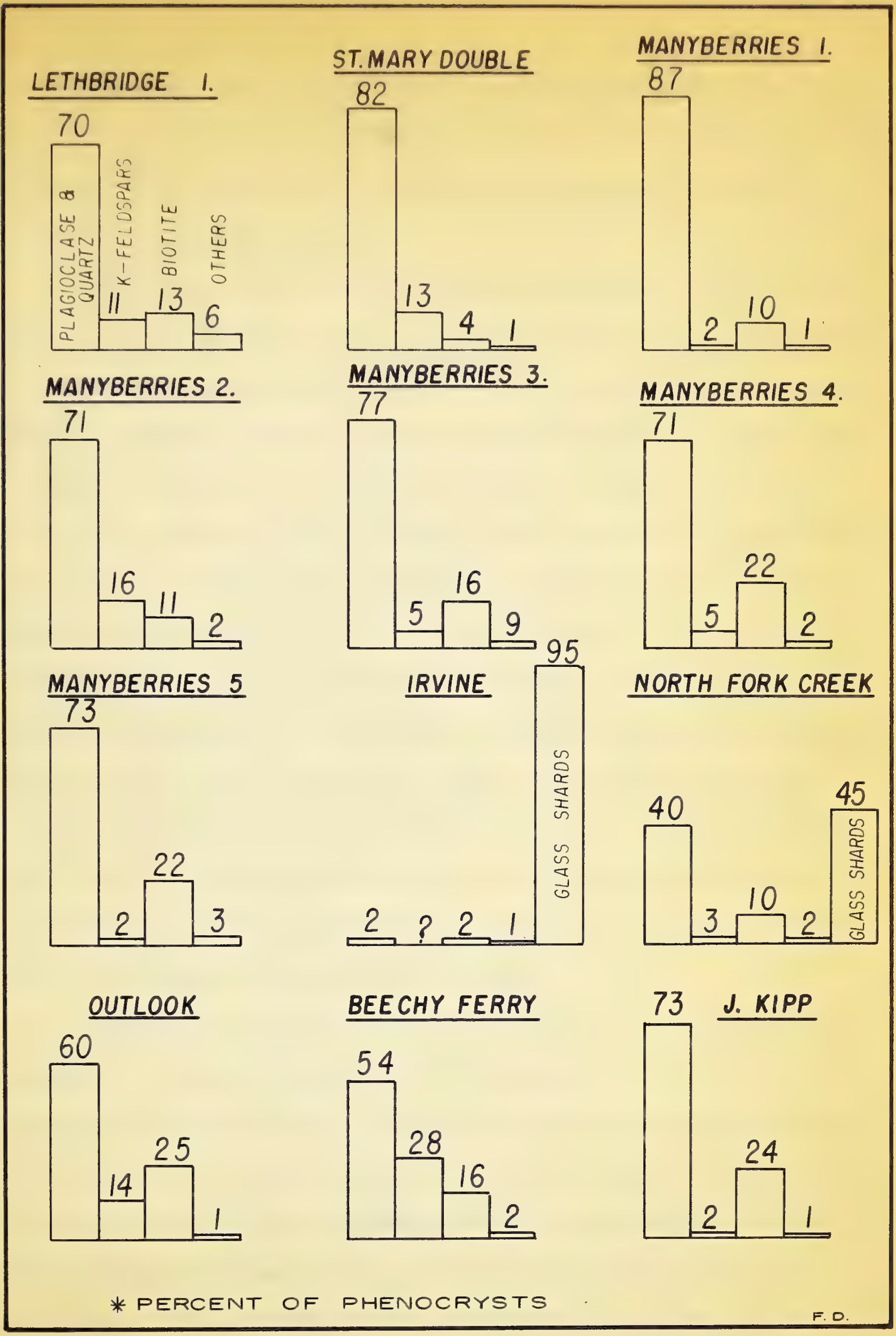

Figure 4. Representative distribution* of phenocryst material in the very fine sand-size fraction of studied bentonites

but in this occurrence glass is the predominant material and crystalline minerals rare. Plagioclases may range in size up to 0.25 mm. (fine sand) and are abundant in almost all size-fractions. However they tend to be concentrated more in the very fine sand fractions (0.125-0.062 mm.).

The plagioclase grains are either clear and unaltered or they are clouded and show incipient alteration along parallel to subparallel fractures. They vary from euhedral to anhedral, fragmented crystals, but on the average they tend to be more euhedral than the alkali feldspars. Columnar to equant shapes are the most common, the columnar being dominant. Twinning according to the albite law is the only twinning which is common, albite-Carlsbad, Carlsbad and pericline twinning being rare or absent in most separates. Zoning is rather infrequent and the cores of the zoned crystals may be more basic than the marginal portions. The plagioclases usually contain frequent to abundant inclusions, consisting either of bubbles or prismatic apatite microlites. Less commonly the inclusions consists of well-formed microlites of zircon, dusty grains of iron oxides, occasional biotite and perhaps hornblende crystallites. The inclusion pattern is generally random but sometimes a partial lineation may be observed with the microlites or bubbles paralleling the pinacoidal or the prismatic zone of the crystals. The typical appearance of plagioclases from the Bearpaw bentonites is shown in Plate I.

Optical examination did not reveal any difference in the composition of plagioclases in the different size fractions. It is probable that almost or all of the plagioclases started crystallizing in the magma chamber at an early stage and that they crystallized mainly as euhedral phenocrysts including many of the available first formed crystallites. Differentiated groundmass-plagioclases do not seem to have been formed. The plagioclase crystals in the smaller fractions of the ashy material might be simply the result of greater shattering of essentially homogeneous

early phenocrysts during the volcanic outburst. The composition of the plagioclases of the studied bentonites is indicated in Table III.

The method adopted for the identification of the plagioclases is Tsuboi's method (1923) as reported in Tickell (1931). The lesser and/or the greater indices of cleavage flakes which are parallel either to 001 or to 010 are sought by using immersion media and monochromatic light and the composition is found from the tables given by Tsuboi. In practice it is sufficient to find the lesser index of either 001 or 010 cleavage flakes, regardless of which face is observed, as it happens that the lesser index of a given plagioclase is almost identical for both 001 and 010 flakes. Fairly concordant results were obtained using the curves of Crump and Ketner (reported in Wahlstrom, 1955) for the composition-refractive indices relationship of cleavage fragments lying on the 001 face. Since the basal cleavage of plagioclases is better developed than the pinacoidal 010 cleavage, when fragments are placed in immersion liquids many of the flakes tend to lie on the basal cleavage and will be recognized by showing a single set of cleavage fractures paralleling the albite-twin lamellae.

Potassium feldspars

Sanidine is by far the most abundant alkali feldspar present within the Bearpaw bentonites. This mineral may form up to 28 per cent of the coarse fraction of the bentonites, but the average content is much less. The maximum sanidine grain size is 0.25 mm. (fine sand) but most of the material is in the very fine sand (0.125-0.062 mm.); little sanidine is found in the size fractions less than 0.062 mm. Sanidine is the high temperature form of orthoclase and resembles orthoclase in most of its properties. It is distinguished by the much smaller optic angle, smaller than

TABLE III PLAGIOCLASE COMPOSITIONS OF STUDIED BENTONITES

	Sodic andesine 30–40 An		Calcic andesine 40–50 An		Lesser and greater indices of cleavage flakes parallel to 001	Optic angle (2V)	Optic sign
	An 30	An 35	An 47	An 49			
Lethbridge 1			x		$\alpha' = 1.552$ $\gamma' = 1.557$	80°–85°	+
St. Mary Double bent.	x				$\alpha' = 1.543$ $\gamma' = 1.549$	85° (?)	-
Manyberries 1			x		$\alpha' = 1.552$ $\gamma' = 1.557$	85°	+
Manyberries 2	x				$\alpha' = 1.543$ $\gamma' = 1.550$	80°–85°	-
Manyberries 3				x	$\alpha' = 1.554$ $\gamma' = 1.558$	80°	+
Manyberries 4				x	$\alpha' = 1.554$ $\gamma' = 1.558$	80°	+
Manyberries 5			x		$\alpha' = 1.552$ $\gamma' = 1.556$	80°–85°	+
North Fork Creek				x	$\alpha' = 1.554$ $\gamma' = 1.558$	80°	+
Outlook	x				$\alpha' = 1.543$ $\gamma' = 1.550$	80°	-
Beechy Ferry		x			$\alpha' = 1.546$ $\gamma' = 1.554$	85°	-
J. Kipp				x	$\alpha' = 1.544$ $\gamma = 1.558$	80°	+

that of any other feldspar. It is a mineral characteristic of magmas which have crystallized at high temperatures. Anorthoclase has a composition intermediate between pure potassium feldspar and albite (over 63 per cent albite) and though it shows gradational optic properties to sanidine it is triclinic (pseudomonoclinic). Its optic angle varies from low values with low content of sodic molecules to about 45° with higher albite content. In the Bearpaw potassium feldspar-separates some crystals have optic angles higher than for normal sanidine (but not as high as for orthoclase) and this suggests the presence of crystals of a mixed alkali feldspar akin to anorthoclase, or the beginning of inversion to orthoclase. Sanidine occurs in the Bearpaw bentonites as 001 and 010 cleavage fragments, platy to irregular in outline. Rounding of crystals by magmatic corrosion is present although not common. Sanidine is mostly unaltered and contains fewer inclusions than plagioclase, which is sometimes clouded with alteration products.

Quartz

With the microscope procedure employed quartz is very difficult to differentiate consistently from the clear varieties of plagioclase showing neither twinning nor cleavage, except through use of optic axis figures. Staining techniques are of uncertain value and no more accurate than optic axis identification, due to the relative abundance of clay coatings on quartz. Quartz occurs in some of the examined bentonites as irregular, angular grains, clear and devoid of inclusions. The character of the grains seems to point out a volcanic origin for the mineral, which is directly derived from the ash falls. The phenocrysts may have been greatly shattered by the explosion. In a few shale separates taken adjacent to the bentonites the quartz examined is abraded, with pitted surfaces and is rich

in inclusions. Undulose extinction is always more common in these detrital quartz grains.

Though no good estimate of the quartz content can be made optically, the study with optic axis figures indicates that quartz in the Bearpaw bentonites is scarce or absent. When present (in about half of the examined samples) the amount of quartz is not larger than five per cent of the total feldspar-quartz content.

Volcanic Glass

Relict glass, in the form of much-clouded and brown-stained irregular aggregates showing polarized particles under the microscope, has been observed in several of the examined bentonites, but glass shards of a relatively unaltered nature and in considerable amount are found only in two of them. The shards resulted from the disruption and fragmentation of a viscous mass of magma, rich in volatile components, when it was explosively erupted. The gases contained in the magma were rapidly released at the surface and the gas bubbles expanded and exploded fragmenting the wall material into shards.

The coarse material of the ashy bentonites of the basal Bearpaw sampled at Irvine is almost entirely composed of glass (over 95 per cent). The other occurrence of a glass rich bentonite is in the Eastend Formation at North Fork Creek. In this latter occurrence the glass shards are more altered, devitrified and stained than those of the Irvine bed. Incipient devitrification is evidenced by a clouded or mottled appearance of the glass and by an abundance of polarizing particles. As may be expected, in beds of different stratigraphic position the glass differs in several respects. In studying the Late Tertiary ash falls of Kansas, Swineford and Frye (1946) used the characters of the shards; shape, color, and

specific gravity as useful guides in differentiating rocks of different horizons. In some respects this would be possible also in the case of the present bentonites. Different indices of refraction for the glass indicate a different SiO_2 composition. The index is 1.504 for the Irvine glass which corresponds to a composition of about 70 per cent SiO_2 and 1.496 for the North Fork Creek glass to which corresponds a SiO_2 content of about 73 per cent (George, 1924). At North Fork Creek the shards contain numerous mineral inclusions as well as liquid and/or gas filled vesicles, at Irvine the only inclusions observed are vesicles. Among the mineral inclusions abundant magnetite grains and small but distinctly euhedral, well-formed crystals of apatite, zircon and titanite have been observed. Other differences between the two glasses have not been noted. In both cases the color is similar, ranging from colorless to pinkish, and the shape of the fragments is also identical. They are mostly dense, subquadrate or elongate plates and lath-shaped fragments with fibrous structure. Arched or crescentic ribs or ridges often mark the surface of the plates.

Heavy Minerals:

Biotite

Biotite is ubiquitous in the examined Bearpaw bentonites and may make up as much as 25 per cent of the coarse material of the bentonite although it is usually present in lesser amounts. The biotite is always of the volcanic variety as evidenced by the euhedral or subhedral flakes and the frequent well-formed pseudo-hexagonal crystals (Plate I). The hexagonal crystals vary from almost equilateral hexagons to elongated hexagons with two parallel sides more developed than the others. The color is usually dusky yellowish-brown or olive brown, but thick flakes appear nearly opaque except around the edge. Inclusions are neither frequent nor uncommon

and consist generally of short prism-like microlites of apatite. On the slide the crystals are non-pleochroic, lie on the 001 cleavage plane, and yield well-centered pseudo-uniaxial negative figures. Corrosion embayments, sometimes filled with glass have been observed in a few cases. In general the biotite appears fresh and unweathered under the microscope. From optical observation it seems that all of the biotite was derived from volcanic ash material. Biotite of other origin was not recognized under the microscope, but in one case an anomalous old K/Ar date from biotite (Irvine) seems to point out the unrecognized presence of older detrital mica, in small amount perhaps, but nevertheless sufficient to cause an older date for the rock.

Hornblende

Phenocrysts of common hornblende are present in one of the studied bentonites (North Fork Creek) but hornblende microlites may be found included in the plagioclases of several others of the examined bentonites. The phenocrysts occur as elongate 110 cleavage fragments, display moderate yellow green (X) to green (Z) pleochroism and inclined extinction ($c \wedge Z$) of about 14°. They usually present dentate terminations and appear rather altered. It is thought that hornblende phenocrysts were originally present also in the bentonites the plagioclases of which include the hornblendic microlites, but that such phenocrysts might have been progressively dissolved through intrastratal solution.

Hypersthene

The orthorhombic pyroxene hypersthene occurs as strongly pleochroic, pink to green cleavage fragments with parallel extinction. Orthorhombic pyroxenes are often found in rock consolidated from basic and ultrabasic magmas but they may be

found also as essential components of extrusive or effusive rocks of dioritic type such as the Ellensburg volcanics of the Cascade Range of Washington (Folinsbee, personal communication). In the Bearpaw bentonites the grains are mainly angular, although often corroded by intrastratal solution. As no attrition by transport seems to be indicated by the habits of the grains the hypersthene can be considered reasonably as a volcanic mineral of the Bearpaw ash falls.

Apatite

Apatite occurs as long to short prismatic crystals terminated by pinacoid or low pyramid. The grains are colorless and often contain liquid inclusions and/or unidentified microlites, either paralleling the c-axis of the mineral, or randomly arranged. The crystals are frequently broken. Intrastratal solution or surface weathering are indicated by corrosion and rounding of many grains. Apatite is present in most of the examined bentonites, its maximum grain size is up to 0.25 mm. but the average grains are between 0.062 and 0.044 mm. (coarse silt fraction). In bentonite No. 1 of Manyberries the apatite is absent and it is also rare in the Outlook bentonite. Solution, and not original scarcity of the mineral, is thought to be responsible for the removal of apatite from the sediments.

Titanite

Titanite is present in two of the sampled bentonites, at Beechy Ferry and at North Fork Creek. In the Beechy Ferry sample titanite constitutes a rather large portion of the heavy minerals being more abundant than all minerals but biotite. The mineral occurs as diamond-shaped euhedral crystals but often the grains are broken and are marked in that case by pronounced conchoidal fracture. The color

is usually pale yellow, the birefringence is very high so that the same color is ordinarily displayed either in ordinary light or under crossed nicols. Due to the very high dispersion characteristic of titanite many grains fail to show complete extinction when rotated under crossed nicols and such grains yield interference figures marked by a large number of color bands. The presence of abundant titanite may be possibly used to differentiate or correlate bentonites at different locations.

Magnetite

Magnetite is present in trace quantity in most of the samples and the plagioclase very often includes magnetic dust. The crystals of magnetite are opaque with a black-bluish luster in reflected light and are distinctly ehuedral in most cases. Frequent dodecahedral crystals have been observed.

Ilmenite

This mineral is present as opaque well-formed to rounded grains, less magnetic than magnetite. The crystals are usually thick tabulae with prominent basal planes and small rhombohedral facets.

Zircon

Zircon euhedra are present in variable amounts in all the heavy mineral crops separated from the Bearpaw bentonites, with the single exception of the Irvine ash-bed. The zircon usually is most abundant in the 230-325 mesh fraction (coarse silt size) and this is certainly due in part to the tendency for the slender, more elongate crystals present in the residue to pass, during sieving, through the 230 mesh by reason of their minimum dimension. The zircons are predominantly colorless and exhibit the following forms: First order and/or second order prisms, simple or

complex pyramidal terminations, pinacoidal terminations. The pyramidal terminations are more common than the pinacoids. Prismatic faces predominate in most crystals and the elongation of crystals is therefore mainly dependent on the relative development of the prismatic faces. In most samples it is possible to recognize three groups of zircons according to crystal morphology:

1. A group of very short, stubby euhedra, often suboval in shape, exhibiting poor development of the prismatic faces. Length-breadth ratio is less than 2.

2. Stubby, intermediate euhedra having length-breadth ratios lying between 2 and 4.

3. Definitely elongate, rod-shaped to needle-like euhedra. Length-breadth ratios in the crystals of this group exceed 4 and may range up to 8.

Broken euhedra are commonly found in the separates and they may belong to any of the aforementioned groups but are more frequently of the third type. The difference in crystal habit for the groups of zircons are by no means clearly understood. Different generations of zircon may be caused by several circumstances resulting in alteration of the physico-chemical conditions existing in the magma at different stages of its evolution (Poldervaart, 1956). Gradual emplacement of the magma at successive levels in the crust may be one possible explanation. It seems logical to assume that elongate crystals began to form first in a magma chamber at great depth, and that stubbier, smaller crystals separated successively when the magma had reached shallower levels. This hypothesis seems to be in agreement with the observation that zoned or corroded crystals are more frequent among the elongate than among the short crystals. Crystals rounded or etched by magmatic resorption or zoned euhedra are present in the crops although not abundant. Most zircons are sharply angular, clear euhedra. As mentioned above resorption and zoning are more

frequent in the long prism type but also the shorter crystals exhibit some degree of rounding of their edges and terminations. In some occurrences they assume a sub-ovaloid shape. The long prismatic crystals sometimes display solution notches or "nibbles" in the side of the prism. Many zircons exhibit inclusions which may or may not show a preferred orientation parallel to the c-axis. The inclusions usually consist of rod-shaped apatite cristallites and equally if not more abundant gas and/or liquid bubbles.

Zircon elongation study

Several characteristics of zircon including color, habit, zoning, inclusions and general shape have been used in zircon studies. Although such characteristics may be of some aid in pointing out petrogenetic relationships among rocks, i.e. similar cooling history in magmas of the same type, they do not seem sufficient to identify with certainty rock masses derived from the same magma and studied at different outcrops (Spotts, 1962). The same applies to correlation of a single ash-fall at two different localities by use of qualitative zircon studies. More significant to the purpose are quantitative studies of the morphological characters of zircon involving elongation data (Poldervaart, 1956). Ritchie (1957) was able by statistical determination of length-breadth ratios of zircon to prove the identity of an Upper Cretaceous tuff-bed in Alberta (Kneehills Tuff) at widely separated outcrops. Spotts (1962), by mean of zircon elongation studies, correlated isolated granitic outcrops in the Coast Ranges batholith of California. Several methods of statistical representation for zircon measurements are available, either histograms or frequency curves. Recently Larsen and Poldervaart (1957), Hall and Eckelmann (1961), and Spotts (1962) have represented quantitative elongation data for zircon by the method of reduced major axis. In general, similarity of elongation frequency

curves are taken as indicative of relationship between two rocks and their possible development from the same magma. In the present thesis statistical studies of zircon elongation have been made on a number of zircon separates. The method of frequency computation which has been used is that described by Smithson (1939) and by Orr (1959). Unfortunately not all the separates are equally suitable for zircon analysis, either because of high percentage of broken euhedra or simply because of the scarcity of zircon crystals in the separate. Usually the size fraction between 270 and 325 mesh has been investigated, this fraction commonly yielding the most abundant zircon crop. In two samples the 170-270 mesh fraction has been analysed. In most cases, the length and breadth of 200 crystals were measured in each sample with a micrometer ocular and mechanical stage applied to the petrographic microscope. All the zircons encountered in each of several fields at regularly spaced intervals on the slide were measured, but broken crystals were excluded from the count. The size characteristics of each zircon crop are quantitatively represented by three separate curves, length, breadth, and elongation or length-breadth ratio (Figure 5). The zircon elongation curves shown for the Bearpaw bentonites are definitely polymodal. Trimodal curves show modes corresponding to the three generations or groups of euhedra mentioned during the qualitative description of the zircon. Some samples are bimodal and have modes corresponding roughly to the first two groups, needle-like crystals are present but do not cluster to form a third modal class. The curves for North Fork Creek, Manyberries 4, Manyberries 3, and Manyberries 1, represent zircons of successive bentonites from a single stratigraphic section. The differences between the curves are too wide, however, to indicate any positive relationship even between these closely spaced bentonites. On this basis the curves could suggest a different source for each ash fall and/or slightly different petrographic magma types. Among the curves representing ash falls of possibly equivalent stratigraphic position such as Lethbridge 1 and the Manyberries series of samples, little correlation is found, thus excluding any positive identity of the beds.

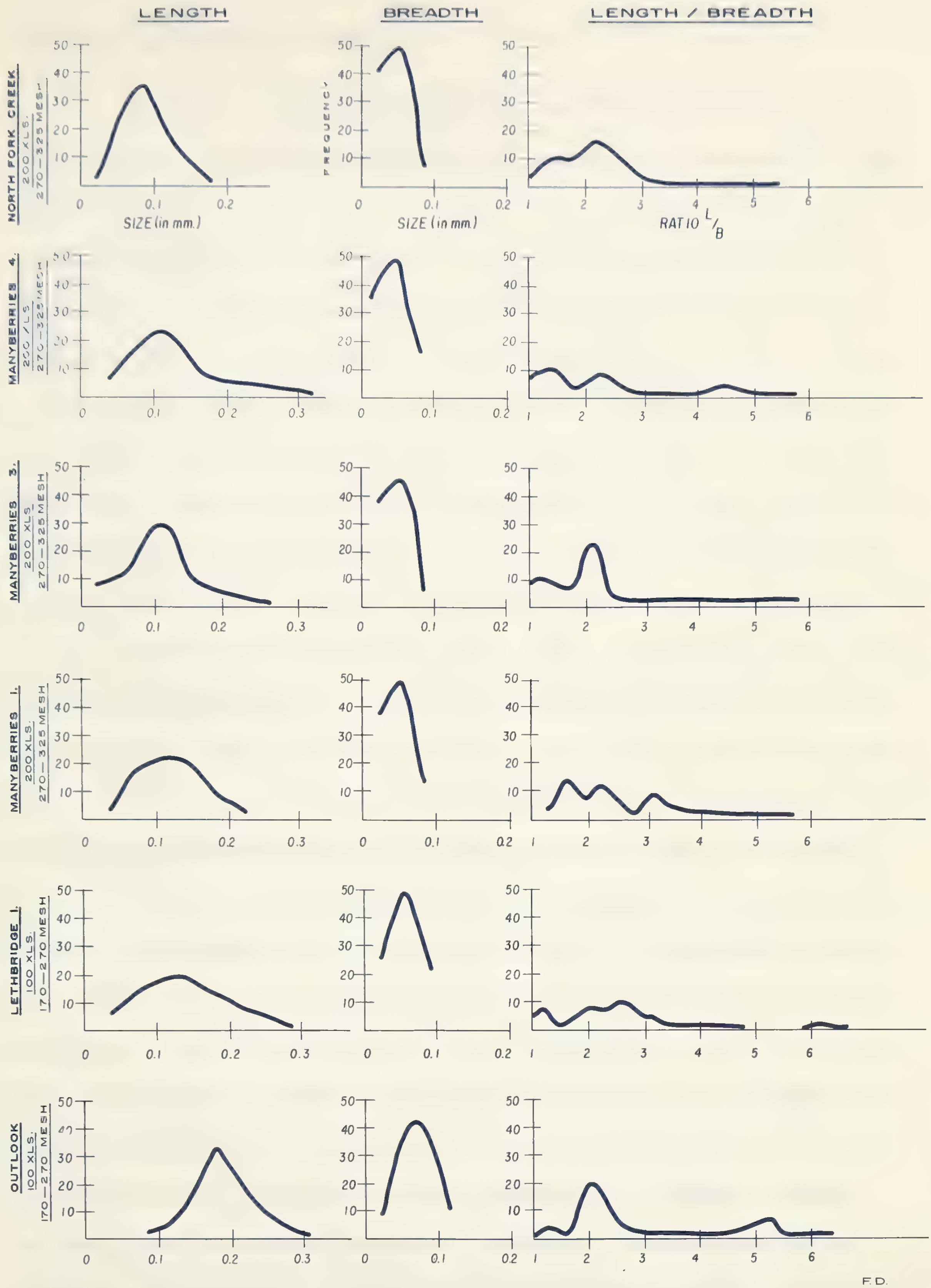

Figure 5. Zircon size-frequency curves of representative Bearpaw bentonites

Detrital and "accidental" Minerals

In tuffs, ultimately the source rocks of bentonites, the volcanic crystals may have derived from three principal sources, according to Pirsson (1915). They may have been formed in the magma itself (essential components) or they may have originated from the older lavas of the volcanic cone (accessory components) or finally they may have had their origin from the shattered rocks of the substratum through which the volcanic conduit was opened (accidental components). Carozzi (1960) suggests, that to determine which origin the crystals of a particular mineral in a tuff may have, two features should be considered. The first is to "determine the general petrologic nature of the tuff and estimate if such a mineral could be considered one of its normal components." He reports to this purpose the example of a trachytic tuff in which crystals of quartz were regarded as foreign to the magma and originated from the walls of the volcanic vent. The second criterion to adopt is the peculiarity that individual crystals may show depending whether they are magmatic or of a different origin. Abundant inclusions, euhedral habit, embayments and magmatic corrosion are good indication that a crystal was derived from the magma. The accessory and accidental crystals which were embedded in solid rocks should be usually more strongly shattered than the essential components. Nevertheless it is somewhat doubtful that a discrimination might be drawn on such evidence because the explosions which produced the tuffs may have affected the magmatic crystals as well as the accidental and accessory ones, and differentiation would be based on an uneasy appreciation of the degree of fragmentation. It is known that a part of the crystals of a tuff or bentonite may also derive from addition of detrital minerals, especially if the rock has been subjected to some degree of reworking. Detrital minerals, either derived from metamorphic, sedimentary or igneous terranes are usually rounded by abrasion and commonly of more stable nature than the volcanically contributed material. Metamorphic and often sedimentary minerals are also differentiated by the fact that they are not normal components of a "magmatic" assemblage of

minerals as it has been mentioned before. Not uncommonly, however, the detrital minerals may have derived from erosion of lavas or igneous rocks, so that it may be difficult to be sure which portion of the minerals of a bentonite is "magmatic" and which portion is detrital, especially if abrasion has not been very intense. Again the mineralogic relations between the various components of the crystal suite, the appearance of the individual minerals or some degree of abrasion may be used as an aid in solving the problem.

From field observations, such as absence of lamination and sharpness of contacts with the adjacent shale beds, it has been already hinted that the Bearpaw bentonites are mainly in situ deposited rocks and that any degree of contamination by detrital material should be negligible. This assumption has been proved to be correct by the microscopic study of the crystal material contained in the rocks. The detrital or accidental material is absent or present in negligible amount in the examined samples. The minerals which are thought to be detrital are described as follows:

Muscovite

Muscovite occurs as thin, colorless, basal plates with a moderate relief in Canada balsam mounts. The plates yield generally well-centered interference figure with a 30° - 35° optic angle and negative optic sign. It is present in most of the bentonites of the basal part of the Bearpaw Formation in the Lethbridge and in the Cypress Hills areas. It looks rather fresh and not abraded so that it could be an accidental component of ash materials erupted from a common source region.

Epidote

Epidote occurs as equidimensional, rounded grains of characteristic greenish-yellow color. Birefringence is high and many grains have a distinct pleochroism from colorless to pale greenish-yellow. Some grains do not show pleochroism and such grains

yield off-center "compass needle" interference figure (2V very large). Epidote is present in trace amount in some of the Bearpaw bentonites and the trace of attrition seen in almost all the grains seems to indicate definitely their detrital origin.

Garnet

A few irregular grains of detrital garnet are present in the crystal suite of the Lethbridge bentonite. The mineral is identified by its pale pink color, its isotropism, high relief and conchoidal fracture.

Rutile

Present in trace amount in one occurrence (St. Mary double bentonite bed) is recognized by its grains characteristically rich in inclusions, its reddish-brown to brown pleochroism and its very high relief and high birefringence which causes the mineral to have the same color in ordinary light as under the crossed nicols. The grains are strongly abraded.

Authigenic minerals

Authigenesis in the bentonites is essentially a reaction and redistribution of material within the rock during diagenesis and leads to segregation of the minor constituents into nodules and concretions or to the formation in place of new minerals. Metasomatism with introduction of material from without the sediment occurs commonly and is considered here as part of the authigenesis process. Calcite, gypsum and barite are the common authigenic minerals of the bentonites.

Barite

Barite is always present in the examined separates. It is also commonly found as nodular concretions in the shale contiguous to the bentonites. The habit of the

barite varies from irregular ragged grains made turbid by clay inclusions to sharply angular cleavage fragments (Plate III). The typical habit, the inclusions and the absence of any large amount of detrital material in the separates leave no doubt that this mineral is authigenic. The cleavage flakes usually lie on the 001 plane and show the diagnostic 78° angle between the prismatic cleavage traces. Grains lying on the prismatic cleavage plane 110 yield a moderate optic angle and positive optic sign.

The abundance of barite in the bentonites, as well as in the shale, present the problem of the source of relatively large amounts of barium in the Bearpaw sediments. Barium, it is known, is extensively substituted for potassium in igneous rocks. This behaviour is well explained by consideration of the ionic size of barium (Ba^{++} 1.43 Å) which permits partial diadochous substitution for potassium (ionic size K^{+} 1.33 Å). In igneous rocks therefore, potash feldspars and biotite often contain significant amounts of barium. During the crystallization of these minerals from a melt the crystals first to consolidate are relatively rich in barium, while crystals formed during the later stages of solidification are progressively poorer of this element until essentially barium free crystals are separated (Rankama and Sahama, 1949). In the volcanic vitreous tuffs the normal process of slow crystallization is abruptly arrested by the sudden cooling of the magma during the effusion and when, perhaps, the barium has not yet been used-up to a large extent by the rare early formed potassium-phenocrysts. Barium, therefore is still abundant in the glass and upon subsequent hydrolysis and bentonitic alteration of the vitreous material, might in part be able to migrate into the sediments as bi-carbonate, chloride and sulfate. Barium is strongly absorbed by the hydrolyzate sediments during the formation of clay and only a negligible amount should be finally precipitated from the weathering solutions as a distinct barium mineral. The problem becomes one of balance between the amount of barium furnished to the sediment, the amount absorbed by the clay and the barium left in the migrating solutions. Migration of barium-bearing waters should be considerably reduced by the impervious nature of

the bentonites. It seems, however, that some transfer of barium solutions must have taken place from the bentonites into the surrounding shale if the bentonites were the source for all the barium in the sediments. It cannot be excluded however that the barium has been introduced from sources outside the ash-beds.

Calcite

This mineral is present as a fine, turbid aggregate with typical high birefringence. It usually occurs coating phenocrysts or glass shards, but is also present as larger, homogeneous anhedral crystals. In this latter case the grains often display rhombohedral cleavage and have extinction symmetrical to the cleavage traces. Calcite aggregates might include clay material.

Gypsum

Gypsum is present as tabular, rhombic or lath-shaped grains, often fibrous, colorless or clouded with clayey inclusions. It is characterized by its low specific gravity and low refractive index. Large crystals, often with herringbone twinning, are common in both bentonites and adjacent shales.

Limonite

Limonite is occasionally found as irregular aggregate grains of earthy, reddish-ochre appearance in reflected light. It may be a weathering product of iron-rich minerals.

Petrologic classification of the bentonites

The most obvious basis for classification of the bentonites is offered by the mineralogy of the coarse fraction. Pure bentonites, such as those of the Bearpaw, contain igneous minerals in the "grit fraction" that were phenocrysts of the original tuff.

Little or no detrital material is present. It is natural, therefore, to attempt a classification based primarily on the phenocryst content, using a scheme adapted from igneous rock classification. The classification used here is based mainly on the presence or absence of quartz and the type and relative proportions of feldspar phenocrysts. In such classification the assumption has been made that the phenocryst content is representative of the glassy or fine-grained groundmass as well, which is frequently not true for volcanic rocks. In general there will be a tendency for the phenocryst material to indicate a more basic rock than the groundmass. Differential sorting, during transport and settling of the ash, should have had a negligible effect in altering the relative proportions of the phenocryst minerals where only quartz and feldspars are involved. Slaughter and Early (in press) in the bentonites of the Mowry Formation of Wyoming have observed some variations in feldspars for the same bed at different levels and different localities but they conclude that probably the variations are due to inhomogeneity in the material erupted. In general the type of classification proposed gives a fairly close determination of the igneous rock equivalent of the bentonite and it is accurate enough to permit the correlation of the original ash-fall with a parental magma. Chemical analysis and a chemical classification (modified to fit into a normative system as, for instance, the CIPW) may be used when the original material is mostly unaltered as in ash-beds. The scheme of classification by phenocrysts for fine-grained rocks in the andesite to rhyolite series, and their coarse-grained equivalents, is given in Table IV. The limits of each rock group have been established from modal data, taking into account those deviations in modal analyses to be expected in extrusive rocks (Slaughter and Earley, in press).

The phenocryst analyses for the studied bentonites are indicated in Table V. As shown, the bentonites have compositions which vary from dacitic to andesitic, with the andesitic bentonites being the average type. Comparatively high alkali feldspar,

TABLE IV ROCK CLASSIFICATION SCHEME OF BENTONITE BY PHENOCRYSTS

(Modified after Slaughter and Earley, in press)

Quartz*	< 10	< 10	> 10	> 10	> 10	> 10
Alkali feldspars**	< 33	> 33 < 66	> 66	> 13 < 33	> 33 < 66	> 66
Andesine**	> 30	> 15	< 15			< 5
Extrusive (Fine-grained)	Andesite	Latite (Trachyandesite)	Trachyte	Dacite	Quartz Latite (Rhyodacite)	Rhyolite
Intrusive (Coarse-grained)	Diorite	Monzonite	Syenite	Granodiorite	Qtz. Monzonite (Adamellite)	Granite

* Per cent of total phenocrysts

** Per cent of total feldspars

TABLE V PHENOCRYST COMPOSITION OF BEARPAW BENTONITES

Locality	Quartz*	Alkali Feldspars**	Sodic Andesine**	Calcic Andesine**	Biotite*	Others	Rock group name from phenocrysts
Lethbridge No. 1		14		86	13	Hypersthene (Hornblende+)	Andesite-Hypersthene Andesite
St. Mary Double bed	<10	14	86		4		Dacite (Andesite ?)
Manyberries No. 1	<5	3		97	10		Andesite
Manyberries No. 2		13	87		11	Hypersthene	Andesite
Manyberries No. 3		6		94	16		Andesite
Manyberries No. 4		8		92	22	Hypersthene	Andesite-Hypersthene Andesite
Manyberries No. 5	<5	3		97	22		Andesite
North Fork Creek	<5	6		94	18	Hornblende	Andesite
Outlook		19	81		25		Andesite (Trachyandesite ?)
Beechy Ferry		35	65		16	(Hornblende+)	Trachyandesite-Latite
J. Kipp	<5	3		97	24		Andesite

* Per cent of total phenocrysts

** Per cent of total feldspars

\+ Present only as inclusion in plagioclase - Phenocrysts might have been removed by intrastratal solution.

with low quartz content, indicate trachytic affinity and in this respect most of the bentonites could be more specifically classified as trachyandesites. In general the figures given for the quartz content are approximate; they indicate only the upper limiting modal value. Greater accuracy was not obtained because grain-counting and the optical technique adopted to differentiate quartz from plagioclase did not permit exact estimates. The approximation, however, provided the limits for modal quartz are not exceeded, is sufficiently accurate for purpose of classification. High ferromagnesian mineral content (high biotite content, and/or presence of amphibole and pyroxene) is taken to indicate appreciably high magnesium content typical of intermediate-basic rocks. In this regard a rock with low biotite content, such as the St. Mary double bentonite, might be considered somewhat more acidic than the average and is classified as equivalent to a dacite.

Particularly interesting and perhaps very significant is the remarkable uniformity of petrologic type in all the studied Bearpaw bentonites. It appears possible to recognize an "andesitic facies" in the lower part of the Bearpaw, which might extend also to the middle and upper portion of the formation. The scatter of samples is as yet too great to allow any positive generalization. The data collected so far, however, show that andesitic bentonites are dominant, if not exclusive, in the whole of the Bearpaw section. That significant variations in the petrology do not occur in bentonites, which were deposited during an appreciable interval of geologic time, is a remarkable fact. It may suggest that the volcanic ash incorporated in the Bearpaw was derived from a single eruptive center which remained active, except for brief intervals, at least during the entire Bearpaw time and was not undergoing, during this period, significant magmatic differentiation.

CHAPTER FOUR

GEOCHRONOLOGY

Bentonites, by reason of their unique lithologic character and mineralogy, may be recognized and traced over wide areas. Time equivalence in deposition makes them exceptional time stratigraphic markers. The absolute age may be determined for the phenocryst minerals of a bentonite if, when they were formed, they included a naturally radioactive nuclide. The age may be calculated from the quantity of the radioactive parent element present today, its decay constant, and the quantity of the radiogenic daughter that has accumulated in the mineral in geologic time. In ash-fall products, for all practical purposes, time of crystallization and time of deposition coincide with the time of eruption. The dating of the bentonite minerals is therefore the best method to calculate the age of the immediately adjacent normal sediments. Confidence in the radiometric date is enhanced by obtaining concordant dates (within the limit of experimental error) for cogenetic minerals and by the use of different methods of age determination.

Much geologic information may be obtained by dating the bentonites intercalated within a normal sedimentary sequence of strata. The geologic "events" represented by the strata are referred to the absolute time scale and may be correlated with "events" in distant basins. A stratigraphic age may be sometimes assigned to an igneous intrusion or extrusion in no other clear way related to a sedimentary series, by studying their petrographic and time relationships to a stratigraphically well defined series of bentonites.

Potassium-Argon age determination

Potassium minerals, commonly biotite and sanidine, are widespread in bentonites. Essentially pure biotite and sanidine are obtained by using the separation methods described in a previous section. The potassium-argon method of age determination has been widely adopted in conjunction with studies of bentonites as time-stratigraphic markers. At the University of Alberta the K^{40}/Ar^{40} method has now been used with a variety of rocks and minerals in the investigation of several geological problems (Folinsbee et al., 1961 - Baadsgaard et al., 1961, - Burwash et al., 1962). Recently the method has been described in some detail by Peterman (1962). A summary of the principles, analytical procedures and calculations used for the radiometric age determinations of the present thesis is given in the following paragraphs.

Dating equation

The radioactive isotope K^{40} occurs to an extent of 0.01207 weight per cent in natural potassium (or 0.01181 atomic per cent). Potassium 40 has a branching decay scheme and yields both argon and calcium

$$
\begin{array}{lll}
Ar^{40} & & \\
\uparrow & & \\
\text{electron capture} & & \text{decay constant} = 0.589 \times 10^{-10}/\text{yr.} \\
/ & & \\
K^{40} & & \\
\backslash & & \\
\beta^{-}\ \text{emission} & & \text{decay constant} = 4.76 \times 10^{-10}/\text{yr.} \\
\downarrow & & \\
Ca^{40} & &
\end{array}
$$

K^{40}-Ar^{40} decay is the basis for potassium-argon dating. K^{40}-Ca^{40} decay is not used as a geochronometer because of the abundance of normal calcium 40 in nature (Rankama, 1954).

The basic function underlying the K-Ar dating method is the function:

$$d N = - \lambda N \, dt \qquad (1)$$

where the rate of decay of an active isotope (and the rate of accumulation of the daughter isotope) depends on the number of atoms N of the parent, and its decay constant λ . For potassium, by reason of its branching decay, only a fraction of the whole K^{40} will go to Ar^{40} in a certain time t. The fundamental relation for the K^{40} - Ar^{40} decay, after derivation, will become

$$Ar^{40} = K^{40} \frac{\lambda_e}{\lambda_e + \lambda_\beta} \left(e^{(\lambda_e + \lambda_\beta)\, t} - 1\right) \qquad (2)$$

from which the final formula used in the age computation is obtained:

$$t \text{ (years)} = 4.308 \times 10^9 \log \left\{1 + (Ar^{40}/K^{40}) \, (9.08)\right\} \qquad (3)$$

Potassium analysis

Potassium has been determined gravimetrically along with rubidium by the tetraphenylboron precipitation method.* Rubidium was determined by X-ray fluorescence analysis, and its value subtracted from the gravimetric potassium value.

Argon analysis

Radiogenic Ar^{40} has been isolated from the potassium minerals by flux-fusion. An aliquot of the mineral is fused with NaOH flux and the gas released is allowed to mix with a known quantity of Ar^{38} from a "spike", and is then passed through a purification system to separate argon from other gases. The argon is finally trapped on charcoal cooled by liquid nitrogen and is ready for mass spectometric analysis.

The mass spectrometer** measures the abundance ratios of Ar^{40}, Ar^{38}, Ar^{36} present in the gas sample. Since argon determinations are made by dilution with Ar^{38}

*Analyses by Rock Analysis Laboratory, University of Alberta. Analyst: A. Stelmach.

**Mass spectrometric analyses by Dr. H. Baadsgaard. Mass spectrometer used a 60° Nier type mass spectrometer (Physics Dept., University of Alberta).

any contaminating atmospheric argon (Air argon Ar^{40} 99.6 - Ar^{38} 0.06 - Ar^{36} 0.34 per cent) may then be determined from the spike Ar^{36}/Ar^{38} ratio and hence "radiogenic" argon Ar^{40} from the air Ar^{40}/Ar^{36} ratio. A correction for any residual argon present in the mass spectrometer tube is made by obtaining, before each run, a "residual blank" (simply a run with no sample in the mass spectrometer), and is subtracted directly from the total readings obtained for the sample-run.

The isotope ratio indicated by the mass spectrometer does not truly represent the isotopic composition of the sample. The discrepancy is caused by the mass discrimination for the particular spectrometer setting adopted. The measured isotope ratio differs from the true value by a factor which is usually close to unity. This mass discrimination factor is calculated by comparing the ratio Ar^{40}/Ar^{36} as determined by the mass spectrometer on a sample of air with the true known value of 295.5 for atmospheric argon (Nier, 1950). The measured ratios Ar^{38}/Ar^{40} for the sample argon are corrected by the appropriate factor.

The volume of radiogenic Ar^{40} is calculated as follows:

$$Ar^{40} \text{ cc STP/gm} = \frac{\text{cc STP } Ar^{38} \text{ (spike)}}{\text{gms. sample } Ar^{38}/Ar^{40}}$$

Volume of Ar^{40} and per cent of K_2O are finally transformed into p.p.m. Ar^{40} and K^{40} and used in the age determination formula (3).

Argon samples have been run with both static and dynamic technique. Deviations in the Ar^{38}/Ar^{40} ratios with the two different procedures is small, usually not larger than few per cent. A value averaged from both static and dynamic Ar^{38}/Ar^{40} ratios has been used for the calculation of the dates.

The Bearpaw bentonite-dates

Twenty-three dates from fifteen Bearpaw bentonites at different stratigraphic horizons and several localities, and one from a bentonite in the Eastend Formation, have

been tabulated in Table VI. Some of the dates were obtained in the course of previous preliminary investigations by Drs. Folinsbee and Baadsgaard. In the majority of the cases the mineral dated is biotite. Six dates have been obtained from sanidine, cogenetic with the biotite.

The analytical results for potassium and argon measurements are assumed to be accurate enough to yield reasonably reliable dates. Investigation of the reproducibility and accuracy of the analystical results with the procedures for potassium analysis employed at the Rock Analysis Laboratory at Alberta, have showed that the maximum deviation to be expected in the dates by this cause usually does not exceed one or two per cent (Baadsgaard, personal communication).

Air contamination during extraction of Ar^{40} may influence the final date. Appreciable deviation in the dates is produced by an air contamination in excess of 30% (Baadsgaard et al., 1957; Hurley, 1961), and increases rapidly with greater contamination. In general, however, the radiogenic argon yields for the minerals analyzed have been fairly high, hence contamination effect should not be too critical in this particular suite of samples.

The biotite and sanidine separates used were generally fairly uniform in size. No critical particle size effect, therefore, should enter the final results. Only for a single bentonite, Lethbridge No. 1, different size-fractions of biotite have been dated. The dates remain essentially constant. Shafiqullah (1963) has discussed to a certain extent the effect of grain size on K-Ar dates and has concluded that in most cases there may be a relationship between the apparent age and grain-size, but the effect is usually small.

A total maximum deviation in the dates of $\pm$ 5% is assumed as the most reasonable value when all the possible analytical causes of error are taken into account.

TABLE VI K-AR DATES OF BIOTITES AND SANIDINES FROM BEARPAW BENTONITES

Horizon and Reference Number	AK-No.	Mineral and Size (Mesh)	K^{40} p.p.m.	Radiogenic Ar^{40}%	Ar^{40}/K^{40}	Dates m.y.
Lethbridge No. 1 Bent. (1)						
	AK 129*	Sanidine 100-270	3.04	77	0.00461	77
	AK 132*	Biotite 60-100	7.03	80	0.00440	73
	AK 131*	100-170	6.67	93	0.00438	73
	AK 130*	170-270	6.28	75	0.00433	72
St. Mary River Tuff (2)						
	AK 314*	Sanidine 60-120	13.19	77	0.00427	71
	AK 313*	Biotite 35-120	6.65	62	0.00413	71
St. Mary River Double Bent. (3)						
	AK 310*	Sanidine 120-230	9.31	82	0.00404	68
	AK 309*	Biotite	2.63	44	0.00427	71
St. Mary River Uppermost Bent. (4)						
	AK 336*	Sanidine 60-120	9.73	83	0.00411	69
	AK 335*	Biotite 150	6.27	54	0.00373	62
Manyberries No. 1 Bent. (5)						
	AK 430	Biotite 120-170	8.51	94	0.00359	70
Manyberries No. 2 Bent. (6)						
	AK 431	Biotite 120-170	7.72	89	0.00440	73
Manyberries No. 3 Bent. (7)						
	AK 432	Biotite 120-170	6.07	94	0.00407	68
Manyberries No. 4 Bent. (8)						
	AK 433	Biotite 120-170	4.60	89	0.00410	68

TABLE VI - Continued

Horizon and Reference Number	Ak - No.	Mineral and Size (Mesh)		K^{40} p.p.m.	Radiogenic Ar^{40}%	Ar^{40}/K^{40}	Dates m.y.
Sucker Creek Bent. (10)							
	AK 334*	Biotite	45-120	6.41	81	0.00392	66
Belanger Creek Bent. (11)							
	AK 351*	Sanidine	120	13.26	77	0.00420	70
	AK 329*	Biotite	35-80	7.28	84	0.00402	67
North Fork Creek Bent. (12)							
	AK 436	Biotite	120-170	8.33	86	0.00387	65
Irvine Ash-bed (13)							
	AK 447	Biotite	120-170	5.88	79	0.00556	92
Outlook Bent. (14)							
	AK 438	Biotite	120-170	7.33	97	0.00417	70
Beechy Ferry Bent. (15)							
	AK 437	Biotite	120-170	8.31	93	0.00412	69
J. Kipp Bent. (16)							
	AK 338*	Sanidine	45-325	9.41	72	0.00413	69
	AK 337*	Biotite	35-170	8.28	72	0.00430	72
Hell Creek Park Bent. (17)							
	AK 308*	Biotite	60-120	7.93	77	0.00420	70

* Dates from previous investigations

Biotite as a dating mineral

Biotite has been the dating mineral most extensively used in conjunction with the present investigation. Biotite, having a good argon retention (Goldich et al., 1961) is a reliable mineral for K-Ar dating. Retentivity of argon is a fundamental requisite for the application of the potassium-argon method. But even biotite, when subjected to severe alteration processes, may lose its argon by diffusion along discontinuities of the lattice. Weathering, accompanied by substitution of water for potassium within the crystal lattice, tends to transform the biotite into hydrated mica or vermiculite. The crystal lattice however remains stable and the optical properties vary slowly during the initial stage of alteration. In this respect all the studied biotites appear optically fresh. Studies of the effect of weathering on micas (Lowdon, 1961) have suggested that partial chloritization has little effect on dates. Kulp and Basset (1961), however, have shown that argon may be lost from weathered biotites together with potassium. Some biotites, therefore, though apparently fairly fresh by normal optical investigation, might have lost a part of their argon and this will result in a young date for the mineral. The biotite of Manyberries 3 and Manyberries 4, for example, have returned dates which appear somewhat young when compared with the dates of other stratigraphically related bentonites. The mineral in the samples looks fairly fresh, but potassium analysis however, indicates possible K-leaching with respect to the biotite of the adjacent bentonites. This would suggest that argon was lost differentially and that the minerals are updated.

The date obtained from biotite at Irvine, on the contrary, is too high to be geologically reasonable. It is suspected that detrital, older biotite may have been washed into this bed.

Results

The bentonite dates provide information of the utmost interest. Much detail perhpas, is yet to be achieved, but it is already possible, on the basis of geochronological evidence alone, to draw a very significant picture of the sequence of events occurring during the sedimentation of the Bearpaw. The results obtained strengthen confidence in the geochronologic approach to this type of investigation. A simple evaluation of the possible analytical and geological errors (contamination, faulty sampling, weathering) appears accurate enough to ensure distinction between "reliable" and "unreliable" dates. The analytically "reliable" dates are compatible with the picture obtained by independent geological means. As shown in Figure 3 the group of bentonites of the lower part of the Bearpaw Formation are intercalated with definitely marine shale, immediately overlying the continental sediments of the Belly River. The dates indicate that the deposition of the basal Bearpaw strata was isochronous over most of the area of the southern Alberta Plains and occurred 72-73 million years ago. In northern Montana the deposition of Bearpaw marine sediments may have initiated somewhat earlier. If the basal portion of the Bearpaw of southern Alberta is time-equivalent to beds higher in the section in Montana, as the James Kipp bentonite date of 72 m.y. seems to suggest, the lower limit of the formation is slightly but definitely diachronous in a north west-south east direction. In the South Saskatchewan River valley area the basal Outlook bentonite has given a date of 70 m.y. from a single dated biotite. This date is assumed to indicate only a minimum value and further dating will be necessary to provide an acceptable age. As mentioned in a previous section, on the basis of geological evidence (Caldwell, in press) it appears probable that the lower 120 feet of Bearpaw section in this area are time-equivalent of Belly River strata to the west and hence should have been deposited at a somewhat earlier date. By a reasonable extrapolation it is possible to demonstrate that the Bearpaw Sea began to withdraw from

the western part of the Alberta basin about 68 m.y. ago. At a time 67 m.y. ago, on the other hand, marine Bearpaw muds were still being deposited in the Cypress Hills area. At 65 m.y. continental sediments had already been laid down for an appreciable period of time in what is now the Cypress Hills area. It seems a reasonable assumption that the sea withdrew definitively from this part of the basin approximately 66 m.y. ago.

The rate of deposition of the Bearpaw sediments in southern Alberta, calculated by dividing thicknesses by K-Ar time-intervals, is in the order of 100-150 feet m.y. Folinsbee et al. (1961) have calculated a comparable, uniform rate of sedimentation both in the Alberta and Peace River basins during the whole Upper Cretaceous. It is interesting to note that the thickness of the Bearpaw shales decreases from the Cypress Hills towards northern Montana where the Bearpaw Sea is known to have transgressed earlier and persisted later. The rate of sedimentation must have been, therefore, slower in the inner parts of the basin than in the marginal areas. It is unfortunate that the geochronological data are still too scanty to allow any more detailed evaluation.

CHAPTER FIVE

PROVENANCE

Volcanism associated with the early Laramide orogenesis in the Cordillera

In folded mountain regions, such as the western mountain system of North America, igneous activity is everywhere broadly contemporaneous with orogenesis. During late Cretaceous time in the region of the Rocky Mountain belt volcanic outbursts and related intrusive activity accompanied the early Laramide folding of the chain. Igneous activity continued intermittently throughout Tertiary time (Baadsgaard et al., 1961) and its products are to be seen today along the various ranges of the Rocky Mountains and in the borderland immediately to the east. Further into the interior of the basins volcanic material is found, intercalated with the normal sediments, as ash-beds or bentonites. Almost all the Cretaceous formations in the Great Plain basins of Canada and United States are characterized by thick and extensive deposits of volcanic ash and bentonite. These deposits extend eastward into central Nebraska, central South and North Dakota and central Manitoba, and spread southward as far as Colorado. The volcanic beds occur in areas which cover more than 400,000 square miles and have contributed a volume to the normal sediments estimated by Ross (1955) to be more than 5000 cubic miles. The distribution of the beds shows them to have their sources mainly in the Rocky Mountain areas to the west. Beveridge and Folinsbee (1956) and Baadsgaard et al. (1961) on the basis of geochronologic data have suggested that a major phase of batholithic emplacement took place in the Cordillera during mid-Cretaceous time 90-110 million years ago, followed by a later period of intrusions of smaller masses in early Laramide time 82 to 71 m.y. ago. The dates given for the latter phase of intrusions are close enough to the range

of dates obtained for the Bearpaw ash-falls to suggest plausibly that the intrusions and their accompanying volcanism had continued into Bearpaw time. The Bearpaw sediments may have been laid down immediately afterwards, or during the final stages of the early Laramide period of batholithic emplacement in the Cordillera. Volcanic activity must still have been very intense and huge clouds of ash were carried by the winds, which had a prevailingly eastward and north-eastward direction, to contribute to the normal sedimentation in the Bearpaw Sea. The coarser pyroclastic material accumulated as marginal facies, closer to the volcanic sources in the west. It is natural, with this view, to look for the sources of the Bearpaw bentonites among the ancient volcanic centers of the Cordillera. When, as it often happens, the intensive erosion which followed the elevation of the mountains has obscured most of the evidences for the volcanic events at the source, the missing link is sometimes sought and found in the volcanic deposits of the marginal areas. In considering the possible sources for the ash-falls these general facts should be kept in mind. In a volcanic area which has suffered little or no erosion the cones and the associated extrusive rocks, lava flows, tuffs and agglomerates, may yield all the information which is needed. Mineralogical comparison between the distant ash-beds and the volcanics in the source area, as a general rule, is sufficient to suggest a correlation. In many areas, however, after the volcanoes have become extinct and erosion has progressed far enough, there will be left, uncovered at the surface, only the subjacent masses of coarse-grained rocks. Such rocks may bear only a vague resemblance to the volcanic differentiates that poured out at the surface.

The Boulder batholith "volcanism" as a possible source of the Bearpaw ash-falls

Volcanic activity associated with the areal igneous phase which resulted in the emplacement of the Boulder batholith of Montana, is considered here as the most probable source for the Bearpaw ash-falls. The volcanoes which erupted the

ashes do not necessarily coincide with the present geographic distribution of the Boulder igneous rocks "sensu stricto". Every large batholithic intrusion, such as the Boulder, is generally accompanied during some stages of its history by several satellite intrusions and extrusions. Sills, dikes, laccoliths, plugs and volcanic cones are distributed peripherally to the main body, and as one can expect in marginal differentiates show strongly individual petrologic characteristics. The general character of the rocks, however, will indicate that such differentiates are genetically related to the same parental magma. Knopf (1957) has studied in detail the Boulder batholith, a large plutonic mass which extends over a 1100 square miles area in the region of Helena and Butte, Montana. According to Knopf's investigations the batholith is a composite mass that was built-up by successive magmas emplaced in order of increasing silica content. The early and main intrusion consisted of a basic granodiorite. A second granodiorite, a porphyritic granodiorite, a biotite adamellite and finally a biotite granite followed in this order. With the exception of the granite the earlier intrusions are comparatively basic. All the intrusions are relatively alkalic. The main characteristics of the Boulder batholith rocks are tabulated in Table VII. The anorthite content of the plagioclase is assumed to be an index of the petrologic character and evolution of the magma throughout the successive intrusions. As it is easily seen the evolution of the batholith, as measured by the anorthite content in plagioclase, did not advance significantly during the interval between the earlier four intrusions. In terms of the ferromagnesian minerals, however, between the third and the fourth intrusions "the evolution had advanced far enough that only biotite was crystallizing from the magma". (Knopf, 1957). In this regard it might be interesting and significant to compare the chemical analyses of the average biotite adamellite and the glass material of the Irvine ashy bentonite (Table VIII). In the Irvine ash-bed also the only ferromagnesian mineral present is biotite.

TABLE VII

CHARACTERISTICS OF THE BOULDER BATHOLITH ROCKS
(Modified after Knopf, 1957)

Intrusion	SiO_2	K_2O	An in plag.	Normative Plag.	Normative Qtz.	Essential Minerals
I						
Granodiorite	61.14	3.34	47	44	15	Plag., K-feld., qtz., hyperst., augite, biotite, hornblende
Granogabbro	54.63	2.10	55	56	8.6	Plag., K-feld., qtz., hyperst., biotite
II	65.49	3.66	44	39	22	Plag., K-feld., qtz., biotite, hornblende
III	66.14	3.54	40-20	34	22	
IV	71.28	4.29	40	29	33	Plag., K-feld., qtz., biotite
V			30			Plag., K-feld., qtz., biotite (muscovite, deuteric)

TABLE VIII CHEMICAL ANALYSIS OF THE IRVINE GLASS MATERIAL AND BIOTITE ADAMELLITE FROM THE BOULDER BATHOLITH

	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O
*Irvine ash-bed	72.08	12.26	.97	.32	.24	.93	3.08	2.44
**Biotite adamellite from Boulder batholith	71.28	14.50	1.04	1.19	.98	2.25	3.16	4.29

	H_2O^+	H_2O^-	TiO_2	P_2O_5	CO_2	MnO	BaO
*Irvine ash-bed	6.47	.75	.16	.03	-	.04	.16
**Biotite adamellite from Boulder batholith	.43	.13	.26	.09	.10	.06	.11

* Analysis of essentially unaltered glass shards - Scanty phenocrysts present in the rock - Biotite - 2% - Plagioclase 2%

** After Knopf (1957)

As it has been mentioned, the main granodioritic intrusion of the Boulder batholith has been dated by the potassium-argon method at 82 m.y. ago. Rocks from the satellite Marysville stock have yielded dates of 78 m.y. (Baadsgaard et al., 1961). Beveridge and Folinsbee have obtained a K-Ar date of 71 m.y. for the potassium feldspar of a pegmatitic veinlet in the Boulder quartz monzonite. In terms of geological evidence Knopf (1957) has observed that the batholith has intruded and invaded a series of andesitic lavas and tuffs which form pendants in the roof of the batholith and which he correlates with the Adel Mountain Volcanics, with rocks that is, which he considers post-Bearpaw. The Adel Mountain Volcanics are a series of potash-rich lavas occurring on the Missouri River north of the Boulder batholith and stratigraphically resting upon an erosion surface cut across the underlying Two Medicine Formation. Fossils indicate that the Two Medicine is in this area nearly equivalent to the Bearpaw. A great many andesitic tuffs are intercalated with the shales and sandstones which constitute the formation. In short all the evidences seem to support the idea of a period of emplacement for the Boulder batholith which included Bearpaw time, and of a source of andesitic volcanism connected with the intrusive activity and located somewhere at or around the main pluton.

There may be also the possibility that the Adel Mountain Volcanics were erupted, at least in part, during Bearpaw time, as some suggestion has been advanced for a somewhat younger age for this series (Lyons, 1944). If so, the volcanic ashes of the Bearpaw might have had their source in the vents which erupted most of the volcanics in the Big Belt Range. Such rocks are mainly trachybasalts, but several stocks are formed of monzonite and diorite. Of particular interest is a dike of a sanidine monzonite containing 10 per cent of barium sanidine phenocrysts. The other minerals are andesine, biotite, orthoclase, hornblende, augite, apatite and magnetite.

Comparison of recent ash-falls and bentonites

Recent ash deposits are described by Bostock (1952) and by Eaton (1963). The ash deposit of the Quizapu' volcano illustrated (Larsson, 1937) in Figure 6 is characteristically tongue-shaped and presents two thickness maxima, one near the volcanic source and the other on the tongue but displaced from the source by about 350 miles. The deposit extends across the tip of South America from ocean to ocean, a distance of more than 1000 miles. Studies of the distribution of many bentonites have shown them to have patterns very similar to those of the recent ash-falls (Slaughter and Earley, in press). In this light bentonites disconnected from obvious volcanic sources are thought to be analogous in development to the displacement maxima of Quizapu' type ashes. The long-axis of the tongues are determined by the fall trajectory of the ash-particles and are roughly parallel to the direction of the prevailing high-altitude winds at the time of eruption. Wind variability during a single period of eruption and turbulent motion within the ash cloud may influence the configuration of the deposits. In general the regional distribution of ashes transported by the high altitude winds is constant for significantly long periods of time. Slaughter and Earley (in press) have visualized the typical sequence of events which result in the transport and deposition of a volcanic ash-fall as follows:

"An explosion or a group of violent explosions occur in the volcano and huge clouds of exploded and exploding material are driven upward into the atmosphere. The explosions in the cloud continue as it rises. The cloud assumes a flat-topped mushroom or umbrella shape with a more or less tapering stem. The height to which the ash rises may vary from 4 to 30 miles depending on the intensity and character of the eruption. The diameter of the cloud may become 50 miles or more. During and after its ascent to maximum height, ash begins to fall from the cloud. The pattern of distribution of ash which settles from the cloud is controlled by high-altitude wind

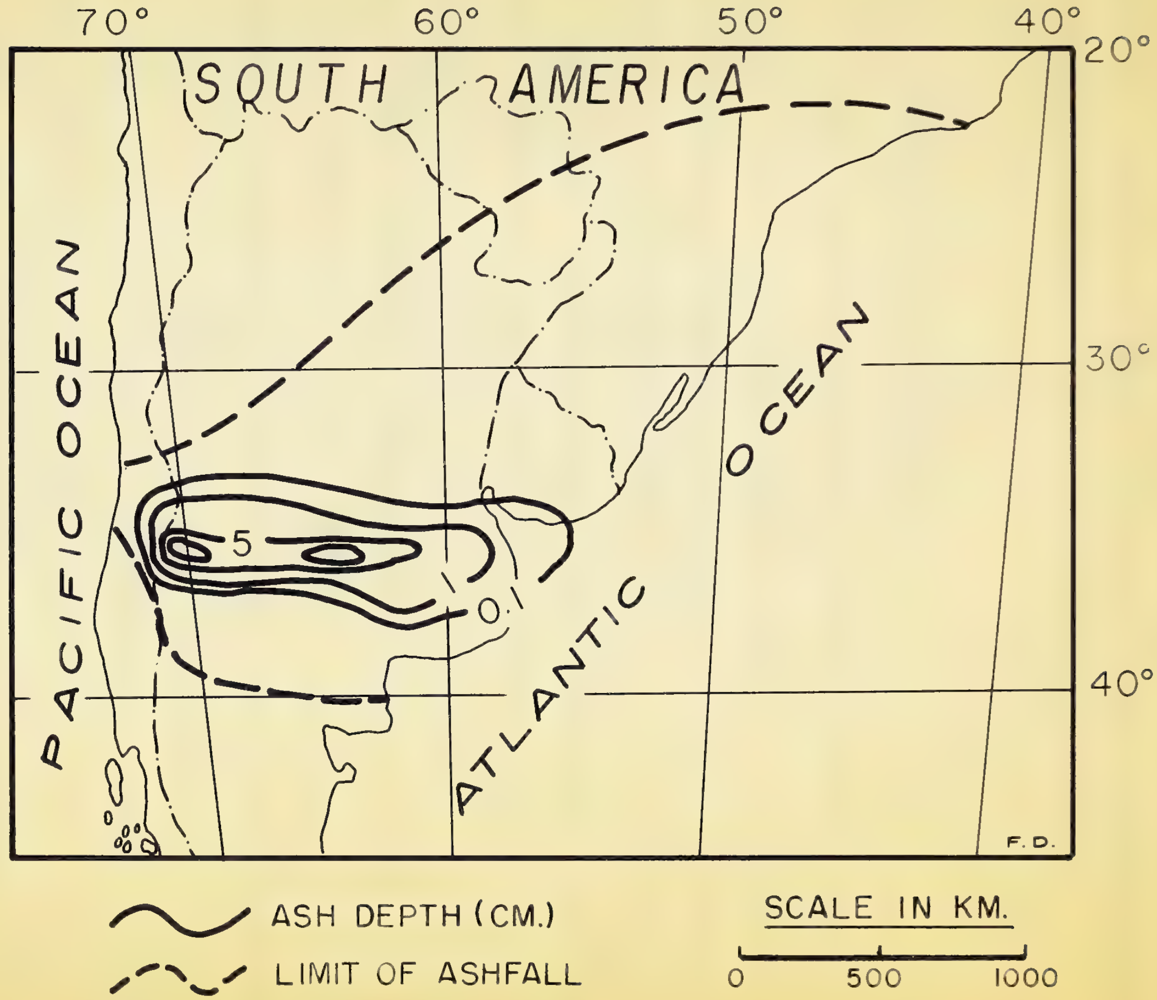

Figure 6. Ash deposit of Recent volcanic eruption-Quizapu' Volcano, Chile (After Larsson, 1937)

directions and, at least for the larger ash particles, by the diameter of the cloud perpendicular to the wind direction. The cloud is very dense compared to the atmosphere and tends to retain its identity for relatively long periods of time. The interior of the cloud is very turbulent, the turbulence decreasing with time after the explosion".

Particle size-distribution of the bentonites

In general the coarse material of an ash cloud should fall closer to the source than the finer material and sorting should improve with the distance and decreasing mean-size of the particles. Size, shape and density of the minerals contained in the ash-cloud should certainly cause some sorting during transportation. The relationship between size, mineralogy and distance from source, however, are only partially known. Mechanical analyses of the bentonites usually disclose some information on the distance of transport of the original ash-fall. The acknowledged limitation of the method is that the alteration of the glass particles to clays has greatly obscured the original size distribution. To use this type of information the assumption is made that the "phenocryst material" reflects the original distribution, including the decomposed glass particles. By simple inspection of the tabulation of the mechanical analyses of the Bearpaw bentonites given in Table IX, it may be seen that the bentonites in question generally have bimodal distribution. The principal mode lies in the clay-size as one can expect for a rock where most or all of the glass particles have been transformed into clays. The second modal class is usually the very fine sand fraction. Sometimes the distribution is unimodal with the modal class in the silt-size fraction. It is uncertain, however, whether this distribution reflects the true distribution of the material or whether it was caused by floculation or incomplete disaggregation of the clays during the analyses. In the ash bed of

TABLE IX MECHANICAL ANALYSIS OF STUDIED BENTONITES*

Bentonite	Coarse fraction				Silt-size	Clay-size	Remarks
	Med. sand	Fine sand	V. fine sand	V. coarse silt			
	Φ 1-2	Φ 2-3	Φ 3-4	Φ 4-4.5	Φ 4.5-8	Φ > 8	
	mm. .5-.25	mm. .25-.125	mm. .125-.062	mm. .062-.044	mm. .044-.0039	mm. < .0039	
	mesh 35-60	mesh 60-120	mesh 120-230	mesh 230-325	mesh < 325		
Lethbridge No. 1	.074**	.218	4.66	2.52	55.4	37.1	
St. Mary Double bed	.014	2.58	10.41	2.9	18.5	65.6	Calcite coatings
Manyberries No. 1		.48	4.87	1.46	13.5	79.6	
Manyberries No. 2		.06	3.3	2.64	9.5	84.5	
Manyberries No. 3		.126	1.79	1.17	5.8	91.1	
Manyberries No. 4		.69	3.99	1.81	7.5	86.0	
Manyberries No. 5		.61	5.36	2.19	15.3	76.6	
North Fork Creek		.025	3.88	4.58	61.5	30.0	Glass shards
Outlook			2.14	2.05	51.8	44.0	
Beechy Ferry		1.20	11.4	4.79	50.6	32.0	Clay lumps ?
J. Kipp	.0036	0.78	5.93	2.55	10.6	80.1	
Irvine		.124	8.18	11.79	65.4	14.5	Glass shards

* Approximately corrected for authigenic minerals. ** Weight per cent

Irvine, which is mainly formed of unaltered glass, the mode is definitely in the silt-size. The scanty phenocrysts consist of biotite flakes and rare plagioclase and are confined to the coarser sizes. A distribution such as this might be caused by differential settling as mentioned before. Nevertheless the possibility that the original scarcity of phenocrysts in the ash was the determinant factor should not be overlooked. The particle size distribution in the studied bentonites definitely indicates that all the air-borne volcanic material which spread over the western Plains during Bearpaw time was consistently fine-grained ash. Significant variations are not observed from one bentonite to the other. The source for all the ash-falls must have been relatively remote. Such uniformity may also lend some support to the idea that all the ashes came from an equally remote, common source.

As summarized by Ritchie (1957), the regional metereologic conditions during late Cretaceous time may have been such as to cause a high atmospheric circulation prevailingly directed northward or northeastward from the assumed source areas in the Cordillera. A warm and semiarid climate in Montana and cooler conditions in the Arctic region have been suggested on the basis of floral evidences.

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APPENDIX

Lithologic description, thickness, location and detailed stratigraphic position of the studied Bearpaw bentonites.

St. Mary River-Lethbridge area

From bottom to top.

BENTONITE No. 1 - Lethbridge
Reference number 1

0.7 foot bentonite-bed, pale-olive when fresh, grey-yellowish when weathered, plastic.

Locality	Valley cliff on west side of the Oldman River. A few hundred yards downstream from the railway bridge at Lethbridge, Alberta. In Lsd. 4 Sec. 1 Tp. 9 R. 22 W4; approximately 112° 52' 20" W-49° 42' 12" N.
Stratigraphic position	About 52 feet above the base of the Bearpaw Formation. The contact between Bearpaw and underlying Oldman Formation is set at the topmost coal-seam of the "Lethbridge Coal Measures". This is bentonite No. 1 of Russel and Landes (1940), "ash bed A" of Link and Childerhose (1931), and bentonite No. 1 of Byrne and Farvolden (1953).

TUFFACEOUS BENTONITE
(LOWER TUFF) - ST. MARY RIVER
Ref. No. 2

0.25 foot tuffaceous bentonite

Locality	Left side cliff of St. Mary River, Alberta. In Sec. 30 Tp. 6 R. 22W4; approximately 112° 57' W - 49° 30' N.
Stratigraphic position	260 feet above base of formation. This might be one bentonite streak in the grey shale above the Magrath fossiliferous beds (Russell and Landes, 1940). It is tentatively identified with the "3 inch ash bed C" immediately above the Magrath sandstone of Link and Childerhose (1931). Byrne and Farvolden (1953) report this bentonite at 262 feet above the base of the formation, at the top of the Magrath Member.

UPPER SEAM OF DOUBLE BENTONITE
ST. MARY RIVER
Ref. No. 3

Upper 0.3 (?) foot seam of a double bentonite bed, that is a bed interrupted by a thin shale interval.

Locality	as above
Stratigraphic position	295 feet above base of the formation. "Double ash bed D" of Lind and Childerhose (1931). Bentonite No. 6 (?) of Russel and Landes (1940). Bentonite at 294 feet above base of the formation (?) of Byrne and Farvolden (1953).

UPPERMOST BENTONITE
ST. MARY RIVER
Ref. No. 4

0.3 foot thick bentonite

Locality	as above
Stratigraphic position	150 feet above "Double bentonite" marker. Tentatively it might be bentonite No. 10 of Russell and Landes (1940). Bentonite No. 9 (?) of Byrne and Farvolden (1959).

Cypress Hills area

From bottom to top.

MANYBERRIES 1
Ref. No. 5

0.6 foot bentonite, greyish-yellow, granular, with rusty streaks.

Locality	East of Manyberries townsite, along gully in Lsd. 9, Sec. 15 Tp. 5 R. 5 W4 Alberta.
Stratigraphic position	67 feet above base of formation. Bentonite No. 1 of Russell and Landes (1940). Bentonite No. 1 of Byrne and Farvolden (1953).

MANYBERRIES 2
Ref. No. 6

1 foot bentonite, moderate greenish-yellow, plastic.

Locality	as above

Stratigraphic position — 9 feet above Manyberries 1 bentonite-bed. Bentonite No. 2 of Russell and Landes (1940). Bentonite No. 2 of Byrne and Farvolden (1959).

MANYBERRIES 3
Ref. No. 7

1.2 feet bentonite, pale green, plastic

Location — as above

Stratigraphic position — 7.6 feet above Manyberries 2 bentonite bed. Bentonite No. 3 of Russell and Landes (1940) Bentonite No. 3 of Byrne and Farvolden (1959).

MANYBERRIES 4
Ref. No. 8

1.2 feet bentonite, moderate greenish-yellow, very plastic

Locality — as above

Stratigraphic position — 15.6 feet above Manyberries 3 bentonite. Bentonite No. 4 of Russell and Landes (1940). Bentonite No. 4 of Byrne and Farvolden (1953).

MANYBERRIES 5
Ref. No. 9

0.25 foot bentonite, greyish-yellow

Locality — as above

Stratigraphic position — 13.6 feet above Manyberries 4 bentonite

SUCKER CREEK BENTONITE
Ref. No. 10

0.1-0.25 foot bentonite, "silty", biotite rich.

Locality — East side of Sucker Creek, a tributary of Belanger Creek, 1/4 mile north of Gilchrist Ranch (Saskatchewan). In Sec. 32 Tp. 6 R. 2W3; approximately 109° 23' W - 49° 30' N.

Stratigraphic position — 4.75 feet below the base of the concretionary zone with *Acanthoscaphites nodosus* in the middle Belanger Member.

BELANGER BENTONITE
Ref. No. 11

0.2 foot bentonite, moderate yellow

Locality	West side of Davis Creek, a tributary of Belanger Creek, Saskatchewan, in the southern half of Sec. 32 Tp. 6 R. 25W3; approximately 109° 20' W - 49° 30' N.
Stratigraphic position	39 feet above the Acanthoscaphites nodosus concretionary zone, Upper Belanger Member.

IRVINE ASHY BENTONITE
Ref. No. 13

1-5 feet mixed ash-bentonite bed, pale greenish-yellow, hard, calcareous.

Locality	1 mile south of Irvine townsite, Alberta. On the right side of highway to Elkwater in Lsd. 9 Sec. 30 Tp. 11 R. 2W4; approximately 110° 16' 15" W - 49° 46' 30" N.
Stratigraphic position	100 feet above the Oldman-Bearpaw contact. Contact drawn at the highest occurrence of lignite.

NORTH FORK CREEK BENTONITE
Ref. No. 12

1 foot bentonite, ashy, pale greenish, somewhat micaceous, hard.

Locality	Along North Fork Creek, Alberta, in Lsd. 13 Sec. 20 Tp. 6 R 2W4.
Stratigraphic position	136 feet above the base of the Eastend Formation, intercalated in the dark grey shale. It might be the "light green to olive green bentonite" in the Eastend composite section of Furnival (1946) and Williams and Dyer (1930).

South Saskatchewan River valley area

From bottom to top

OUTLOOK BENTONITE
ref. No. 14

0.5 foot bentonite, greyish-yellow

Locality	West side of the South Saskatchewan River, 6.7 miles south and 2.5 miles east of Outlook townsite, Saskatchewan, in Tp 28 R. 8W3; approximately 107° 02' W. 51" 22' N.

<u>Stratigraphic position</u> 30 feet above the higher lignitic shale and sandstone of the Oldman. In the Beechy Member.

BEECHY FERRY BENTONITE
Ref. No. 15

0.6 foot bentonite, pale olive, plastic

<u>Locality</u> 150 feet above river level at ferry of Beechy, South Saskatchewan River, Saskatchewan; in north half of Sec. 20 Tp. 20 R. 10W3 approximately 107° 20' W. 50° 43' N.

<u>Stratigraphic position</u> Approximately in the middle of the Snakebite Member, at an estimated distance of 450 feet above the base of the Bearpaw Formation

<u>Northern Montana</u>

From bottom to top

JAMES KIPP BENTONITE
Ref. No. 16

1 foot (?) bentonite, pale olive, plastic

<u>Locality</u> On State of Montana highway 19, west of Fort Peck Reservoir in NW Sec. 11 Tp. 22 R. 24E Princ. Merid.; approximately 108° 41' W - 47° 38' N.

<u>Stratigraphic position</u> About 250 feet above the contact of the Bearpaw with the Judith River Sandstone. Four thin bentonites are present in the 15 feet section just below.

HELL CREEK BENTONITE
Ref. No. 17

<u>Locality</u> On the road to Hell Creek State Park, Montana, 2 miles south of the Picnic site in Sec. 14, Tp. 21N, R. 37E Princ. Merid.; approximately 106° 57' W - 47° 32' N.

<u>Stratigraphic position</u> 100 feet below the upper contact with the Fox Hills Sandstone, Kara Member equivalent ? (Robinson <u>et al.</u>, 1959).

PLATE I - Photomicrographs of plagioclase, sanidine, volcanic glass shards and biotite from selected studied bentonites.

Figure 1. Plagioclase. Note inclusions
Manyberries 4 bentonite. 120-170 mesh
Parallel light, x 25.

Figure 2. Plagioclase, nicols crossed
Manyberries 5 bentonite. 120-170 mesh
x 25.

Figure 3. Plagioclase showing inclusions of apatite microlites.
Manyberries 4 bentonite. 120-170 mesh
Parallel light, x 64.

Figure 4. Plagioclase showing inclusions of biotite microlites, magnetite dust and apatite.
Manyberries 1 bentonite. 120-170 mesh.
Parallel light, x 64.

Figure 5. Sanidine. Note lack of inclusions
Beechy Ferry bentonite. 120-170 mesh
Parallel light, x 25

Figure 6. Volcanic glass shards
Irvine ashy bentonite. 120-170 mesh
Parallel light, x 25.

Figure 7. Biotite
Manyberries 4 bentonite. 120-170 mesh
Parallel light, x 25

Figure 8. Biotite hexagonal flake showing magmatic corrosion embayment.
Manyberries 4 bentonite. 120-170 mesh.
Parallel light, x 64.

PLATE I.

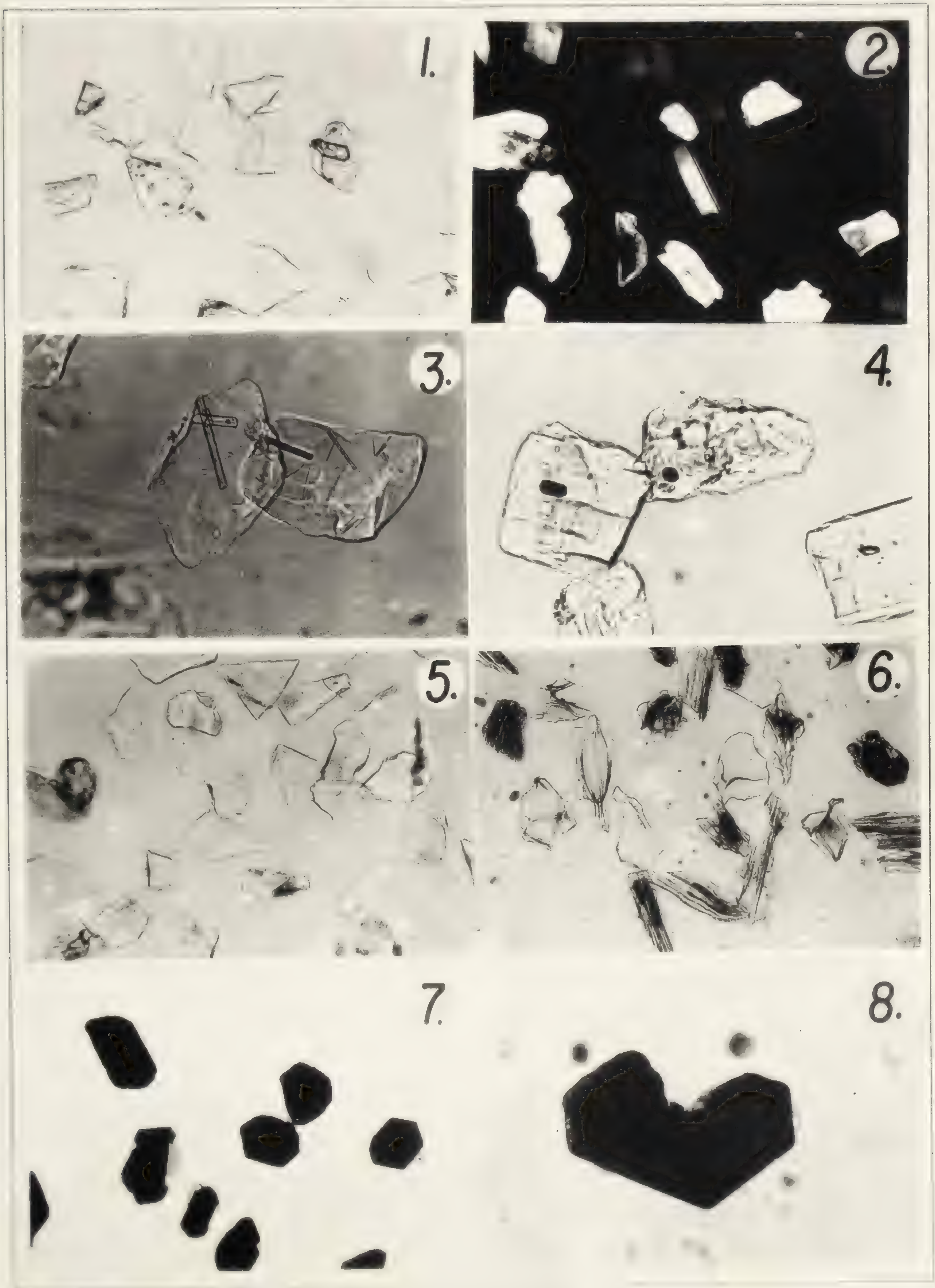

PLATE II – Photomicrographs of hornblende, titanite, apatite and zircon from selected studied bentonites

Figure 1. Hornblende showing dentate terminations
North Fork Creek bentonite. 120–170 mesh
Parallel light, x 64

Figure 2. Titanite. Note diamond-shaped crystal
Beechy Ferry bentonite. 120–170 mesh
Parallel light, x 64.

Figure 3. Apatite showing inclusions
North Fork Creek bentonite. 270–325 mesh
Parallel light, x 64.

Figure 4. Apatite showing inclusion paralleling c-axis of the mineral
North Fork Creek bentonite. 270–325 mesh
Parallel light, x 64.

Figure 5. Zircon. Note the very short-stubby, the stubby-intermediate and the elongate euhedra.
Manyberries 1 bentonite. 270–325 mesh.
Parallel light, x 25.

Figure 6. Short-stubby zircon prisms
Manyberries 1 bentonite. 270–325 mesh.
Parallel light, x 64

Figure 7. "Intermediate" zircon prisms. Note inclusions and magmatic corrosion "nibbles".
Manyberries 1 bentonite. 270–325 mesh.
Parallel light, x 64.

Figure 8. Elongate, rod-shaped zircon prism. Note inclusions and magmatic corrosion "nibble" on side of prism.
Manyberries 1 bentonite. 270–325 mesh
Parallel light, x 64.

PLATE II.

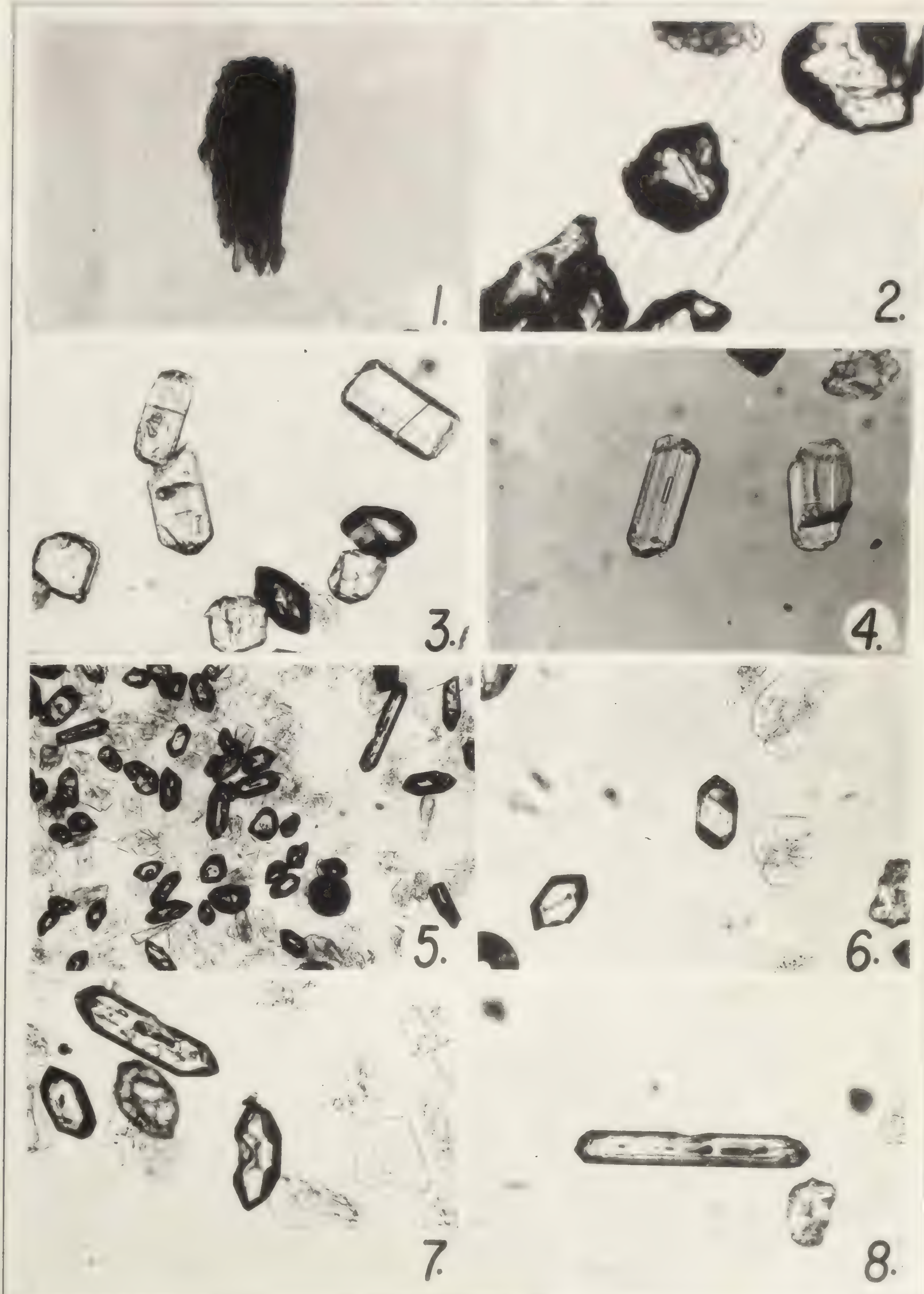

PLATE III - Photomicrographs of zircon, muscovite and barite from selected studied bentonites.

Figure 1. Zircon euhedral crystal showing magmatic corrosion "nibble".
Manyberries 4 bentonite. 270-325 mesh
Parallel light, x 160

Figure 2. Zircon euhedral crystal showing inclusion of bubbles and microlites.
Manyberries 3 bentonite. 270-325 mesh
Parallel light, x 64.

Figure 3. Zircon euhedral crystal showing inclusion of bubbles.
Manyberries 3 bentonite. 270-325 mesh
Parallel light, x 64.

Figure 4. Zircon euhedral crystal showing random inclusions.
Manyberries 1 bentonite. 270-325 mesh
Parallel light, x 160

Figure 5. Muscovite
Manyberries 4 bentonite. 120-170 mesh
Parallel light, x 25

Figure 6. "Ragged" barite grains
Manyberries 1 bentonite. 270-325 mesh
Parallel light, x 64.

Figure 7. Barite. Note the sharply angular cleavage flake of the mineral.
Manyberries 1 bentonite. 270-325 mesh.
Parallel light, x 64.

PLATE III.